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ANALYSIS AND DESIGN PROCEDURES FOR A FLAT, DIRECT-CONDENSING, CENTRAL FINNED-TUBE RADIATOR

by Richard P. Krebs, Henry C. Haller, and Bruce M. Auer

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CONTENTS

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SUMMARY

An analysis of a flat, direct-condensing, central finned-tube radiator rejecting heat from both sides was performed that enabled the design of space radiators to meet minimum weight and geometric requirements. Two electronic digital computer programs were developed. The first program is based on a fixed conductance parameter and yields a minimum weight design. The second employs a variable conductance parameter and variable ratio of fin length to tube outside radius. This program can be used for radiator designs that have geometric limitations. Both programs consider a Rankine thermodynamic cycle, vapor and liquid headers, pressure drop in the radiator tubes and headers, meteoroid protection for the tubes and headers, radial temperature drop in the tube wall, and fin and tube radiant interchange in the development of the descriptive equations.

Major outputs of the two programs include: tube length, number of tubes, radiator aspect ratio, radiator weight, fin length and thickness, specific-heat-rejection rate, and header geometry. These outputs are based on the choice of input variables such as tube inside diameter, temperature and power levels, fin and armor materials, prescribed pressure drops in tubes and headers, mission time and probability of no punctures by meteoroids, and radiator-header-panel configuration.

A 1-megawatt, high-temperature Rankine system was chosen for comparison of the two programs. The maximum heat rejected per unit weight was used as the evaluating parameter. The calculated results showed that the value of the product of the conductance parameter and the apparent emissivity for maximum heat rejection per unit weight, as determined by the Parametric Program, although different from that used in the Minimum Weight Program, resulted in radiator weights that agreed to within 2 percent at maximum heat rejection per unit weight. Radiator planform area, fin thickness, and panel aspect ratio were also investigated and compared favorably.

INTRODUCTION

Large quantities of electric power will be required for a variety of space applications within the foreseeable future. These applications include electric power supplies for satellites, lunar bases, and orbital laboratories, as well as for electric propulsion for interplanetary travel. Due consideration of the design of nonpropulsive power supplies must be given to the weight-carrying and size capabilities of the ferrying vehicle.

The feasibility of many space missions utilizing electric propulsion depends on obtaining a specific weight (powerplant weight/power output) of the power conversion system that is low enough to permit large payload weight and extended missions. Currently, a leading contender for the electric power source is a generator driven by a turbine operating in a Rankine cycle and using a liquid metal as the working fluid. One of the major problems associated with such a cycle is the rejection of waste heat by the radiator.

Previous studies (refs. 1 to 5) have indicated that the required radiator may be a large part of the total conversion system weight. It is also obvious that the space and maximum internal dimensions of the boost vehicle will be limited. It therefore becomes necessary to design lightweight radiators that also satisfy radiator-vehicle integration requirements. Thus, such factors as radiator area and component dimensions as well as minimum specific weight become important considerations.

Many papers on direct-condensing radiators for Rankine vapor cycles are available (i.e., refs. 6 to 12), but none is sufficiently complete nor applicable for setting up a general radiator design computer program. Thus, it becomes necessary to combine and improve the available information into a reasonably thorough approach to the problem. The programs developed can also serve as a basis for the comparison of other approximate or less sophisticated procedures.

The analysis presented herein is a comprehensive approach to the design of direct-condensing space radiators. A cycle analysis is included to provide vapor-flow and heat-rejection rates and quality and to permit the study of the effects of power level and temperature level. Also included in the analysis are the contributions of the vapor and liquid headers along with the pressure drops in the radiator tubes, headers, and junctions. The effect of the temperature drops, which accompany the pressure drop in the tube and at the tube-header junction, is also included. The basic finned-tube configuration chosen is a central-finned constant-diameter tube lying in a flat plane radiating from both sides to a 0° space sink temperature. Provision for consideration of several panel arrangements is also included. The analysis is based on radial one-dimensional heat conduction in the tube and one-dimensional heat conduction down the length of the fin with blackbody mutual irradiation occurring between the fin and tube surfaces. The effect of surface emissivity less than unity is treated by introducing an approximate approach that uses an apparent emissivity of the finned-tube cavity. Meteoroid protection considerations are included for the radiator tubes as well as for the vapor and liquid headers.

Two sophisticated programs evolved from these analyses. The first of these permits a radiator design that will satisfy specific radiator geometry requirements over a wide range of conditions. At the same time the radiator weight can be accurately optimized. This program, henceforth called the Parametric Program, is based on a variable value of a conductance parameter that describes the thermal behavior of the fin. The program requires considerable detail and computer time to obtain a desired radiator design.

The complexity involved in determining an optimum radiator configuration as given by the Parametric Program procedure made it necessary to develop a second program with a more rapid calculation procedure. This procedure, which could be used for preliminary purposes to define the region of interest for a design study, can rapidly investigate the factors influencing radiator design and weight without regard to specifics such as area or fin geometry limitations and requirements. This program, which is based on a fixed value of conductance parameter, is referred to as the Minimum Weight Program.

Both programs treat tube inside diameter, fluid temperature, power level, material properties, mission parameters, tube and header pressure drops, and meteoroid protection criteria as the input variables. Calculations employing these inputs yield the weight and characteristic dimensions of the finned-tube space radiator. The programs are divided into subroutines so that other finned-tube configurations, such as the open or closed sandwich finned-tube geometries (ref. 13), can be adapted without completely rewriting the program.

A sample set of calculations are given for both the Parametric and the Minimum Weight programs. The results are compared for a typical example consisting of a 1-megawatt powerplant radiating waste heat at 1700° R.

SYMBOLS

A area, sq ft

A_p planform area as defined by eq. (111), sq ft

A_v vulnerable area, sq ft

a spalling factor

B radiosity, radiation leaving surface per unit time and area

c sonic velocity in armor material, ft/sec

c_p specific heat, Btu/(lb)($^\circ$F)

D diameter, ft

E_t Young's modulus of tube armor material, lb/sq ft

F geometric angle factor

F_f tube surface effect on fin heat loss

F_t tube radiant interchange factor

$\overline{F}$ occlusion factor

f Fanning friction factor

g units conversion factor, 32.17 ft/sec^2

H enthalpy, Btu/lb

h heat of condensation, Btu/lb

h_{sc} subcooler heat-transfer coefficient, Btu/(hr)(sq ft)(^{o}F)

J mechanical equivalent of heat, 778 (ft)(lb)/Btu

K radiation-distribution parameter, $(\overline{q}_t + \overline{q}_f)/\epsilon\sigma\pi D_i T_o^4$

K_H fluid turning loss factor from header to tubes

K_p fraction of generator output available as power output

k thermal conductivity, Btu/(ft)(hr)(^{o}F)

L fin half-length, ft

L_c condenser length, ft

L_{sc} subcooler length, ft

m constant describing panels

N number of radiator tubes

N_c conductance parameter, $2\sigma T_o^3 L^2/kt$

$\overline{N}$ number of penetrations permitted

n integer

P pressure, lb/sq ft

$P(\overline{N})$ probability of $\overline{N}$ penetrations

P_e electrical power output, kw

Q total heat flow rate, Btu/hr

Q_{in} total heat added to cycle fluid, Btu/hr

Q_{out} work output, Btu/hr

Q_{rej} heat rejected by vapor header and radiator panel, Btu/hr

Q_s	heat rejected by entire system, Btu/hr
q	specific heat flow rate, Btu/lb
$\overline{q}$	heat rejection per unit time and length of tube, Btu/(hr)(ft)
R	gas constant, (ft)(lb)/(lb)($^{\circ}$R)
Re	Reynolds number
R_i	tube inside radius, ft
R_o	tube outside radius, ft
R'	fraction of flow area occupied by one phase
S	entropy, Btu/(lb)($^{\circ}$R)
$\overline{S}$	header surface area, sq ft
T	absolute temperature, $^{\circ}$R
T_o	temperature of base surface of fin and tube, $^{\circ}$R
ΔT_{sc}	amount of subcooling, $^{\circ}$F
t	fin thickness, ft
u	velocity of vapor, ft/sec
V	velocity of liquid, ft/sec
$\overline{V}_p$	average meteoroid velocity, ft/sec
W	weight, lb
$\dot{W}$	total weight flow, lb/sec
$\overline{W}$	ideal work output of cycle, Btu/lb
W'	panel width, ft
w	weight flow per tube, lb/sec
X	dimensionless coordinate, x/L
X'_{tf}	fraction of radiator heat rejected by fin and tubes
X'_{VH}	fraction of radiator heat rejected by vapor header

x	position coordinate on fin, ft
Y	length of vapor header as defined by eq. (52)
Z	tube length, ft
α,β	experimentally observed constants for meteoroid mass distribution
δ	tube wall thickness, ft
ϵ	surface hemispherical emissivity
$\bar{\epsilon}$	apparent emissivity of isothermal finned-tube cavity
η_{act}^*	gray body overall effectiveness
η_f	flat plate blackbody fin efficiency
η_f^*	blackbody fin effectiveness
η_g	generator efficiency
η_r^*	blackbody overall effectiveness
η_t	turbine efficiency
η_t^*	blackbody tube effectiveness
θ	temperature ratio, T/T_o
θ_s	space sink temperature ratio, T_s/T_o
$\dot{\theta}$	$d\theta/dX$ evaluated at $X = 0$
μ	viscosity, lb/(ft)(sec)
ρ	density, lb/cu ft
σ	Stephan-Boltzmann constant, 1.713×10^{-9} Btu/(sq ft)(hr)($^oR^4$)
τ	mission time, days
X,Φ	two-phase-flow parameters

Subscripts:

a	armor
act	actual

b	boiler
c	liner
F	friction
f	fin
g	vapor phase
i	inside
L	liquid
LH	liquid header
m	momentum
o	outside
p	particle
r	radiator panel
t	tube
VH	vapor header
1	base surface 1
2	base surface 2

Superscripts:

(')	between boiler and turbine	(when applied to q or Q)
(")	between turbine and radiator	(when applied to q or Q)
(*)	static conditions at tube inlet	

APPROACH

The primary objective of the computer programs described herein is to afford a means of designing a direct-condensing radiator that would serve as a heat-rejecting device for a Rankine cycle power-generating system of a prescribed power level. Both programs were geared to design radiators that not only matched a prescribed power level but that also gave the designer the capability to set the pressure drops within the radiator. One of the programs provides a radiator design that is near minimum weight for the heat-rejection and pressure-drop specifications. The other has the flexibility of providing for specific area or dimensional requirements.

To make such an objective achievable in a computer program of practical and manageable size, some restrictions had to be placed on the range or generality of the parameters defining the radiator. For example, radiator temperatures are limited to those for which the equivalent sink temperature effect on the heat radiated can be neglected (generally greater than 1000° F, ref. 14).

Some selection was made as to the physical arrangement of the radiator. In this analysis it was assumed that the radiator was made up of a series of fluid-carrying tubes connected by central fins in a flat plane radiating from both sides, as shown in figure 1. The tubes consisted of a liner, which was to be relatively impervious to the corrosive working fluid, and an armor sleeve to protect the liner from the hypervelocity meteoroids encountered in space.

The tubes were fed from a parabolically shaped vapor header designed for constant fluid velocity. A parabolically shaped header provides a weight saving of approximately one-third over a constant diameter header, if the maximum diameters of the two headers are equal. Constant flow velocity in the header tends to make the pressure loss, due to turning the flow from the header into the tube, uniform for all tubes. The header consisted of a liner and a protective armor of the same thickness and material as that used on the tubes. The condensed vapor was collected in a liquid header. The liquid header was constant in diameter and consisted of an internal liner and the same armor covering that was used on the tubes and the vapor header.

The computer programs were written so that the tubes and headers could be arranged in any one of the three configurations shown in figure 2. These arrangements are designated as one-, two-, and four-panel configurations.

To make a study of the factors that affect the design and performance of a direct-condensing radiator, a rather complete analysis was made. This analysis included calculations for the basic power cycle as well as the thermal and fluid mechanics processes going on in the radiator. These processes included the temperature drop in the tube wall, the radiation from the tubes, fins, and headers to space and to each other, and the pressure and temperature changes in the fluid due to friction, change in momentum, and changes in flow direction. The amalgamation of these analyses ultimately resulted in a pair of computer programs that produced a radiator design meeting a prescribed heat-rejection rate and vapor-flow rate with assigned internal pressure losses.

In the first of these, the Parametric Program, the fin geometry could be independently chosen by specifying the ratio of fin half-length to tube outside radius L/R_o, the tube inside diameter D_i, and the conductance parameter N_c. In the second, or Minimum Weight Program, the fin conductance parameter was fixed at a single value for which the fin weight was very near a minimum for a given heat-rejection rate from the fin (ref. 12).

For both of these analyses the power cycle was selected, together with the panel-header configuration (see fig. 2), the inside diameter of the tubes, and the pressure drops. With these data as inputs, the computer programs proceeded to generate a complete radiator design.

The various facets of the radiator design analysis were grouped conveniently into several computer subroutines. The MAIN subroutine takes the properties of the working fluid, the component efficiencies, and the electric power output requirement and computes the cycle fluid flow rate, the radiator heat-rejection rate, and the quality of the working fluid at the turbine exhaust. The MAIN subroutine also reads the inputs and writes the outputs for the entire program. Inputs, other than those required by the cycle, include the physical and thermal properties of the materials used in the radiator and the pressure losses. Outputs include a complete description of the geometry of the radiator, its weight and area, and the specific heat rejection, in Btu per pound, for the fin and tube panel alone as well as for the entire radiator.

After the MAIN subroutine has performed the cycle calculations, the subroutine GUIDE assigns a first approximate value to the heat-rejection rate for the vapor header and to the vapor velocity at the tube inlet. The approximate heat-rejection rate for the header permits an estimate of the heat-rejection rate for the finned-tube panel. The approximation of the tube inlet velocity determines the number of tubes required.

The subroutine SUBW then determines the finned-tube geometry, including tube armor thickness, fin width and thickness, and an approximation to the overall tube length required. The armor surface temperature at the tube inlet is also determined. The determination of the fin geometry is different for the Parametric and Minimum Weight Programs, and the subroutine SUBW constitutes the chief difference in the two programs.

The pressure drop in the radiator tubes is next obtained by subroutine SUBK that uses the initial approximations for velocity and number of tubes. SUBK also determines the actual tube length required for condensing and subcooling the vapor. The length of the vapor header can be determined from the number of tubes and the finned-tube geometry. The diameter is determined from the selected vapor header pressure drop by subroutine SUBH.

Subroutine GUIDE now makes two calculations. First, it determines whether the pressure drop in the tubes is less than or greater than the assigned value. GUIDE then makes an appropriate correction on the inlet velocity to the tubes. GUIDE also computes a new heat-rejection rate for the vapor header based on the previously calculated length and diameter. With the new values of heat-rejection rate and tube inlet velocity, GUIDE calls on SUBW and SUBK to recalculate the finned-tube geometry and the tube pressure drop. This iterative process is continued until the pressure drop matches the assigned value. SUBH then computes the radiator weights, planform area, and aspect ratio, as well as several ratios among the heat-rejection rates and the component and total radiator weights.

BASIC INPUTS AND OUTPUTS

The MAIN subroutine has three functions: (1) to read the input data required for all programed calculations, (2) to write the output tape, and (3) to execute the thermodynamic cycle computations. The inputs are summarized subsequently, while the details of the cycle calculations will be given in the section that follows. For convenience, the inputs required by both programs can be divided into five categories: thermodynamic cycle, working fluid properties, panel configuration, space environment, and materials. The elements of these categories will be briefly described, and the corresponding detailed developments will be given in later sections.

Thermodynamic Cycle Inputs

Eight inputs are required for the cycle calculations. Station locations in the cycle can be identified in the schematic diagram of the cycle (fig. 3) and the temperature-entropy diagram (fig. 4). Inputs include the turbine inlet, or peak cycle temperature, T_1; radiator temperature, $T_3 = T_2$; the amount of subcooling between states 3 and 4, ΔT_{sc}; the required useful electrical power output, P_e; the turbine and generator efficiencies, η_t and η_g, respectively; the fraction of the generator output available as useful power output K_p; and the heat lost by radiation upstream of the turbine, from the turbine casing, and by conduction away from the turbine, q'.

Working Fluid Properties

The properties of the working fluid are required in both the cycle calculations and the pressure drop calculations. The enthalpy and entropy of the saturated vapor and liquid for four liquid metals, obtained from reference 15, were expressed as polynomial functions of temperature. The specific relations used are given in appendix A.

Other properties derived from reference 16 that must be entered as inputs are: the viscosity of the liquid and vapor, the specific heat of both phases, the liquid density, the vapor pressure corresponding to the radiator inlet temperature, and an equivalent gas constant that satisfies the relation $R = P/\rho_g T$ for the vapor over the temperature range encountered in the radiator. Use of the equivalent gas constant permits expressing vapor density differentials in terms of pressure and temperature differentials in the tube pressure drop calculations.

The vapor pressure for potassium originally obtained from reference 16 was compared with that given in reference 17. The two pressures differed by no more than 5 percent over the temperature range from 1400° to 2000° R. The equilibrium specific heats for potassium vapor varied as much as 37 percent between the two references over this same temperature range. No comparison between the frozen specific heats, used in the computation of the two-phase pressure drop, was possible; however, inaccuracies in the specific heat of the vapor are expected to have negligible effects on the computed results because of the narrow temperature range encountered in the radiator.

Panel Configuration

The radiator programs are capable of determining performance, weight, and area for three different panel arrangements of tubes and headers, as illustrated in figure 2. Simultaneous results for four different tube inside diameters can be obtained in one program execution. The tube inside diameters are determined by the following expression

$$D_i = \overline{D}_i + n\,\Delta D_i$$

in which $\overline{D}_i$ and ΔD_i are program inputs and n takes on the values from 0 to 3. For the Parametric Program, two geometric parameters that describe the fins must be included in the inputs. These are the conductance parameter N_c and the ratio of fin half-length to tube outside radius L/R_o.

In both programs the pressure change in the tubes and in the vapor header can be selected. The pressure loss due to turning and accelerating the flow between the vapor header and the tubes is expressed as a multiple of the dynamic head in the tubes by the factor K_H. The liner thickness in the vapor header $(\delta_c)_{VH}$ and the maximum velocity in the liquid header must also be supplied as inputs to the programs.

Meteoroid Protection

Many of the factors that determine the armor thickness required to protect the radiator from meteoroid penetration have to be furnished. Based on the method of reference 18, these include: meteoroid population parameters α and β, density of the meteoroid ρ_p, average meteoroid velocity $\overline{V}_p$, spalling factor a, occlusion factor $\overline{F}$, number of penetrations permitted $\overline{N}$, probability of $\overline{N}$ penetrations $P(\overline{N})$, and mission time τ.

Material Properties

The material properties of the tubes and fins affect the resistance of the armor to meteoroid penetration and heat transfer. Material density is also required to determine the radiator weight. Material properties that must be supplied are: thermal conductivity of the fin and tube k_f and k_t, densities of fin, tube, and liner ρ_f, ρ_t, and ρ_c, respectively, and modulus of elasticity of the tube armor E_t.

Outputs

In the course of the computations, a great many results are computed and transferred to the output tape. Those that appear on the output format will be indicated as they are derived in the analysis. A computer output sheet, showing both inputs and outputs, is included in appendix B. FORTRAN statements for both computer programs are included in appendix E.

CYCLE ANALYSIS

To design a direct-condensing radiator, certain parameters must be known. These include mass-flow rate, heat-rejection rate, radiator temperature, and vapor inlet quality. While it would be possible to develop a radiator design program in which the foregoing parameters were required program inputs, a different procedure was adopted for the programs discussed in this report. Because these direct-condensing radiators were considered a part of a Rankine power generating system for use in space, an analysis of the Rankine system was included in the computer programs, and appropriate results from this analysis were used for the radiator design calculations. Defining parameters for the power cycle thus become the input variables for the computer programs.

The basic power generating system analyzed is shown in figure 3. It consists of a boiler to vaporize the working fluid, a turbine to drive the generator, a radiator to reject the waste heat, a subcooler that is part of the radiator and that lowers the liquid temperature below the saturation temperature, and a pump to circulate the condensed working fluid. The heat source for the boiler need not be specified, but could be a nuclear reactor or a solar absorber, for example. In addition to the heat radiated by the radiator including the subcooler (q_{VH} from the vapor header and q_r from the finned-tube panel), two other heat losses have been included in the analysis. The first q' is the sum of the heat radiated from the boiler by the piping between the boiler and the turbine and from the turbine casing, and the heat conducted away by the supports and turbine bearings. The second q'' is the heat radiated between the turbine exhaust and the radiator. Cooling of components such as the generator and electronic equipment is assumed to be accomplished by a secondary coolant circuit and radiator and thus is not included herein.

In the Rankine cycle (see fig. 4) the fluid leaves the subcooler portion of the radiator at state 4, and is pumped into the boiler (state 5) where heat is added to the liquid at constant pressure until saturation temperature is reached (state 6). Further addition of heat vaporizes the liquid completely (state 1). In this cycle analysis, operation with superheat was not considered. The saturated vapor passes from state 1 through the turbine with a loss in temperature, a decrease in quality, and an increase in entropy to state 2. Heat is extracted from the working fluid at constant temperature to state 3, where all the fluid has condensed. Further extraction of heat in the subcooler reduces the temperature of the liquid to state 4.

Pressure changes other than those in the turbine and the pump have been neglected. Those pressure changes in the radiator have little effect on the thermodynamics of the cycle but are important in the radiator design. Accordingly, that part of the analysis which is devoted to pressure drops in the headers and tubes of the radiator will be detailed in the two sections HEADER DESIGN and RADIATOR TUBE PRESSURE DROP AND LENGTH.

In the derivation of the cycle quantities that follows, it should be noted that two heat flow rates are used: the total heat flow rate, designated by Q and expressed in Btu per hour, and the specific heat flow rate q, that is, the heat flow rate divided by the mass flow rate expressed in Btu per pound. The two are related by $Q = 3600\ \dot{W}q$.

Flow Rate

The heat input to the cycle Q_{in} is equal to the total amount of heat added to the working fluid. Most of the heat is supplied by the boiler Q_b, but some comes from the pump in the amount of $3600\ \dot{W}q_p$. Thus $Q_{in} = Q_b + 3600\ \dot{W}q_p$. The heat input can also be described as the heat required to raise the temperature of the subcooled working fluid to saturation and to vaporize it completely. From figure 4 it can be seen that, in terms of enthalpy and entropy,

$$q_{in} = (H_5 - H_4) + (H_6 - H_5) + T_1(S_1 - S_6)$$

$$= H_6 - H_4 + T_1(S_1 - S_6) \tag{1}$$

and

$$Q_{in} = 3600\ \dot{W}\left[(H_3 - H_4) + (H_6 - H_3) + T_1(S_1 - S_6)\right] \tag{2}$$

The work output, expressed in heat units, is given by

$$Q_{out} = \frac{3414\ P_e}{\eta_g K_p} = Q_{in} - Q_s \tag{3}$$

where Q_s, the heat rejected from the entire system, is given by

$$Q_s = 3600\ \dot{W}(q' + q'' + q_{VH} + q_r) \tag{4}$$

The heat that must be extracted from one pound of turbine exhaust is given by $T_3(S_2 - S_3) + H_3 - H_4$. This heat is dissipated by radiation from the piping between the turbine and the radiator, the vapor header, and the radiator panel and can be expressed as

$$q'' + q_{VH} + q_r$$

Equating these two heat quantities

$$T_3(S_2 - S_3) + H_3 - H_4 = q'' + q_{VH} + q_r \tag{5}$$

and substituting equation (5) into equation (4) give the system heat-rejection rate:

$$Q_s = 3600\ \dot{W}\left[q' + T_3(S_2 - S_3) + H_3 - H_4\right] \tag{6}$$

Then, combining equations (2), (3), and (6) yields the following equation for weight flow:

$$\dot{W} = \frac{0.948\ P_e}{K_p \eta_g \left[(H_6 - H_3) + T_1(S_1 - S_6) - q' - T_3(S_2 - S_3)\right]} \tag{7}$$

The weight flow equation can be further simplified by introducing the turbine efficiency η_t and the concept of the ideal work for the cycle $\overline{W}$. Ideal work can be written as

$$\overline{W} = (H_6 - H_3) + T_1(S_1 - S_6) - T_3(S_{2'} - S_3) - q' - q'' \tag{8}$$

The turbine efficiency is expressed as cycle work output divided by ideal work output, so from equations (2), (3), and (6)

$$q_{out} = H_6 - H_3 + T_1(S_1 - S_6) - q' - T_3(S_2 - S_3) \tag{9}$$

and

$$\eta_t = \frac{q_{out}}{\overline{W}} = \frac{\overline{W} - T_3(S_2 - S_{2'}) + q''}{\overline{W}} \tag{10}$$

If equations (8) and (10) are inserted in equation (7), the result is a useful equation for determining the weight flow in terms of the system parameters. Thus,

$$\dot{W} = \frac{0.948\ P_e}{K_p \eta_g \eta_t \overline{W}} \tag{11}$$

where $\overline{W}$ is defined by equation (8)

Thus far, three quantities appearing on the computer printout sheet (appendix B) have been computed. These are Q_{in} = QIN from equation (2), $\overline{W}$ = WBAR from equation (8), and $\dot{W}$ = WDOT from equation (11). Equation (8) requires only cycle temperatures, thermodynamic properties of the working fluid, and a heat loss, all of which are computer program inputs. With the use of the results of equation (8), the cycle flow rate $\dot{W}$ is computed from equation (11), since the parameters P_e, K_p, η_g, and η_t are all inputs.

Quality at Turbine Exhaust

The vapor quality at the turbine exhaust QUAL2 can be calculated from figure 4:

$$\text{QUAL2} = \frac{S_2 - S_3}{S_{2''} - S_3} = \frac{(S_2 - S_{2'}) + (S_{2'} - S_3)}{S_{2''} - S_3} \tag{12}$$

The entropy difference $S_{2'} - S_3$ is known from the thermodynamic properties of the working fluid, since $S_{2'} = S_1$, and $S_2 - S_{2'}$ can be calculated from equation (10). The denominator $S_{2''} - S_3$ is also a function of the thermodynamic properties. Thus, QUAL2 can be obtained from inputs and equations (10) and (12).

Heat-Rejection Rates

The heat-rejection rate from the system can be computed by combining several relations already developed. Thus, from equation (2)

$$Q_s = Q_{in} - Q_{out}$$

and from the general relation between Q and q

$$Q_s = 3600\ \dot{W}(q_{in} - q_{out})$$

Inclusion of equations (10) and (11) yields

$$Q_s = \frac{3414\ P_e}{K_p \eta_g \eta_t \overline{W}} (q_{in} - \overline{W}\eta_t) = \frac{3414\ P_e}{K_p \eta_g} \left(\frac{q_{in}}{\eta_t \overline{W}} - 1 \right) \tag{13}$$

The heat-rejection rate for the radiator is made up of heat rejection from the panel and from the vapor header:

$$Q_r + Q_{VH} = Q_{rej} = Q_s - Q' - Q'' \tag{14}$$

The division of heat rejection between the panel and the vapor header will be discussed in a later section. In these computer programs Q'' was considered to be zero.

Thermal and Cycle Efficiencies

The thermal efficiency is computed as

$$\eta_{therm} = \frac{\overline{W}}{q_{in}} \tag{15}$$

and the cycle efficiency as

$$\eta_c = \eta_t \eta_{therm} \tag{16}$$

These two efficiencies η_{therm} and η_c appear in the output sheet as ETHERM and ETAC, respectively. The temperature ratio across the turbine appears in the output as T2/T1.

FIN AND TUBE GEOMETRY

In order to determine the cross-sectional geometry of a radiator finned-tube panel, it is necessary to develop equations that describe the panel configuration in terms of the heat-rejection requirements, the tube armor requirements as specified by meteoroid protection considerations, and the magnitude of the vapor header heat rejection. Program inputs required for this phase of the radiator design consist of: the conductance parameter N_c and the ratio L/R_o (for the determination of the overall blackbody effectiveness), tube inside diameter, tube inside wall temperature, finned-tube and vapor-header heat-rejection requirements, and meteoroid protection criteria and property inputs.

The required outputs consist of: the overall blackbody effectiveness, tube wall temperature, tube wall thickness, and fraction of the total radiator heat rejected by the fins and tubes.

Assumptions

The central-finned-tube-radiator configuration considered for the analysis is composed of an inner liner tube, meteoroid protection sleeve, and a rectangular fin as shown in figure 5. The thermal analysis of this geometry considers the general case of a rectangular fin of length L and thickness t attached to a tube whose temperature T_o is constant over the outer surface. Energy input to the fin is comprised of heat conduction along the fin from the fin and tube interface and incident radiation from the two tube surfaces. Radiant emission is from both surfaces of the fin to the surrounding environment.

The specific assumptions used in the development of the fin heat-transfer relations for both the Minimum Weight Program and the Parametric Program are

(1) The radiator surfaces act as gray bodies with incident and emitted radiation governed by Lambert's cosine law.

(2) The space sink temperature is assumed to be zero (see appendix C).

(3) One-dimensional radial heat transfer is assumed through the tube wall.

(4) Steady-state one-dimensional heat flow in the fin is assumed.

(5) Material properties are constant and evaluated at the fin base temperature.

(6) The development of the fin and tube angle factors is based on an infinite length finned tube.

(7) Fin thickness is neglected in the formulation of the angle factors and the tube and fin surface area (ref. 19).

(8) The vapor header emits energy from its full outer surface.

Parametric Program

The Parametric Program analysis treats an approximation to the general heat-transfer case for gray-body emission with mutual irradiation between fin and tube. The exact gray-body analysis, formulated in reference 7, has been shown to be extremely complicated. Reference 7 also presents a simplified approach that assumes all the surfaces act as blackbody radiators and absorbers. This last analysis has been used for the investigation reported herein with the effect of surface emissivity less than unity superimposed on the blackbody solution. The emissivity was handled in an approximate manner that took into account the cavity effect introduced by the tubes and central fin. The cavity analysis is given in appendix D.

Radiating effectiveness. - The heat-rejection rate from the fin per unit axial length is equal to the heat-conduction rate into the base of the fin given by Fourier's heat-conduction equation:

$$\bar{q}_f = -2kt \left.\frac{dT}{dx}\right|_{x=0} \tag{17}$$

If $X = x/L$ and $\theta = T/T_o$, equation (17) may be rewritten in terms of a nondimensional temperature gradient at the fin base:

$$\bar{q}_f = \frac{-4L\sigma T_o^4}{N_c} \dot{\theta}_{X=0} \tag{18}$$

where N_c is defined as the ratio of the radiating potential to conducting potential of the fin and is given as

$$N_c = \frac{2\sigma T_o^3 L^2}{kt}$$

and

$$\dot{\theta}_{X=0} = \left.\frac{d\theta}{dX}\right|_{X=0}$$

The nondimensional temperature gradient at $X = 0$ can be solved from the following equation that describes an energy balance on a differential element of the fin (ref. 7):

$$\frac{d^2\theta}{dX^2} = N_c \left[\theta^4 - \left(F_{X-1} + F_{X-2}\right)\right] \tag{19}$$

The angle factors F_{X-1} and F_{X-2} in equation (19) describe the fraction of energy that leaves a differential element of area $Z\,dx$ on the fin and is intercepted by the tubes. The angle factors may be evaluated from expressions that are the result of a relation which applies to finned tubes of infinite length (ref. 20, eq. (31-58)). This assumption is justified by noting that the finned-tube length Z is generally considerably greater than the fin length L $(Z/L > 10)$. These relations, obtained from reference 7, are

$$F_{X-1} = \frac{1}{2}\left[1 - \frac{\sqrt{\left(\frac{R_o}{L} + X\right)^2 - \left(\frac{R_o}{L}\right)^2}}{\frac{R_o}{L} + X}\right]$$

and

$$F_{X-2} = \frac{1}{2}\left[1 - \frac{\sqrt{\left(\frac{R_o}{L} + 2 - X\right)^2 - \left(\frac{R_o}{L}\right)^2}}{\frac{R_o}{L} + 2 - X}\right]$$

Equation (19) can then be solved for fixed values of L/R_o and N_c to yield θ as a function of X and the value of the slope of θ against X at the fin base $\dot{\theta}_{X=0}$. The slope of the temperature profile can then be used in equation (18) to determine the fin heat rejection.

The blackbody heat-rejection rate from the tube per unit length at a constant outer surface temperature is given by

$$\bar{q}_t = 4\sigma R_o T_o^4\left[1 + \frac{L}{R_o}\int_0^1 (2 - \theta^4)(F_{X-1} + F_{X-2})dX\right] \tag{20}$$

where θ as a function of X is obtained from the solution of equation (19).

The preceding heat-rejection rates for fins and tubes can be expressed as fractions of the heat rate radiated from a blackbody flat plate with infinite thermal conductivity and width equal to $2(L + R_o)$. This reference heat rejection is given as

$$\bar{q}_{ideal} = 4\sigma R_o T_o^4\left(1 + \frac{L}{R_o}\right) \tag{21}$$

The fin radiating effectiveness is then defined as

$$\eta_f^* = \frac{\bar{q}_f}{4\sigma R_o\left(1 + \frac{L}{R_o}\right)T_o^4} \tag{22}$$

where $\bar{q}_f$ is obtained from equation (18). The blackbody tube effectiveness is defined as

$$\eta_t^* = \frac{\overline{q}_t}{4\sigma R_o\left(1 + \frac{L}{R_o}\right)T_o^4} \tag{23}$$

where $\overline{q}_t$ is obtained from equation (20). Thus, the overall blackbody heat-rejection rate per unit length of fin and tube can be written as

$$\overline{q}_r = \overline{q}_t + \overline{q}_f = 4\sigma R_o\left(1 + \frac{L}{R_o}\right)T_o^4(\eta_t^* + \eta_f^*) \tag{24}$$

and the overall blackbody fin and tube effectiveness is then

$$\eta_r^* = \frac{\overline{q}_r}{\overline{q}_{ideal}} = \eta_t^* + \eta_f^* \tag{25}$$

The overall blackbody effectiveness η_r^*, which is obtained from equation (25), is a function of the inputs N_c and L/R_o. Illustrative variations of η_r^* are shown plotted against the ratio L/R_o for several values of the conductance parameter N_c in figure 6.

The approximation to the actual heat radiated $\overline{q}_{act}$ for a gray surface with $\epsilon < 1$ and to the overall gray-body effectiveness η_{act}^* is accomplished by using the concept of an apparent emissivity for the finned-tube cavity in the relations as follows:

$$\overline{q}_{act} = \overline{\epsilon}\,\overline{q}_r \qquad \text{and} \qquad \eta_{act}^* = \overline{\epsilon}\eta_r^* \tag{26}$$

where $\overline{\epsilon}$, as developed in appendix D, is shown plotted against the ratio L/R_o for several values of surface hemispherical emissivity ϵ in figure 7.

Tube wall temperature drop. - The previous relations were all based on the outer tube wall temperature T_o. This value is dependent on the fluid temperature in the tube and on the temperature drop across the tube wall. This temperature drop is dependent on the tube wall thickness, which, in turn, is dependent on the radiator vulnerable area. For purposes of relating the fluid and outer wall temperatures, a simplified approach for determining the tube length and vulnerable area is used that assumes the inside tube wall temperature along the entire tube length is equal to the static temperature of the fluid T^* evaluated at inlet conditions. This assumption also is used in determining the increased tube length required for subcooling. The exact length of the radiator and subcooler tube portions is determined by the pressure drop analysis considered in the section RADIATOR TUBE PRESSURE DROP AND LENGTH.

The relation between the inside and outside tube temperatures is based on a one-dimensional heat balance that assumes heat is rejected from the tube outside surface by radiation only. This equation obtained from reference 21, (p. 82) is given as

$$\frac{\sigma\epsilon(D_i + 2\delta_c + 2\delta_a)}{2} T_o^4 \ln\left(\frac{D_i + 2\delta_c + 2\delta_a}{D_i + 2\delta_c}\right) + k(T_o - T^*) = 0 \qquad (27)$$

This equation assumes a uniform temperature on the inside tube wall and no temperature drop across the tube liner. The temperature T^* is determined from the following expression, similar to equation (70):

$$T^* = T_2\left(1 - \frac{1}{2}\frac{K_H u_0^2}{Jgh}\right) \qquad (28)$$

where T_2 is the radiator inlet fluid stagnation temperature in $^{\circ}R$ and u_0 is the tube inlet vapor velocity. The radiator tube liner thickness δ_c required in equation (27) was made a function of the inside tube diameter given by the arbitrary schedule $\delta_c = 0.04\ D_i$.

<u>Armor thickness</u>. - The tube armor thickness δ_a used in equation (27) is determined by using the meteoroid protection criteria given in reference 18, which is based on a comprehensive and definitive appraisal of the data and theories available concerning the meteoroid penetration phenomenon. According to reference 18, the resultant equation for the armor thickness δ_a is given by

$$\delta_a = 2\bar{F}a\left(\frac{\rho_p\ 62.45}{\rho_a}\right)^{1/2}\left(\frac{\bar{V}_p}{c}\right)^{2/3}\left(\frac{6.747\times10^{-5}}{\rho_p}\right)^{1/3}\left(\frac{\alpha A_v \tau}{-\ln P(0)}\right)^{1/3\beta}\left(\frac{1}{\beta + 1}\right)^{1/3\beta} \qquad (29)$$

where

$\bar{F}$	1.0
a	1.75
ρ_p	0.44 gm/cc
$\bar{V}_p$	98,400 ft/sec
α	0.53×10^{-10} g^{β}/(sq ft)(day)
β	1.34

The total exposed area to be protected A_v is assumed to be the outer surface of the tubes and vapor header. The liquid header contribution is assumed to be negligible since its surface area is small compared with that of the vapor header. Thus

$$A_v = A_t + A_{VH} \qquad (30)$$

The radiator tube vulnerable area A_t is taken as the entire circumferential surface area of the tube and is given by the expression

$$A_t = \pi D_o \overline{NZ} \tag{31}$$

where the approximate total tube length $\overline{NZ}$ is defined by the expression

$$\overline{NZ} = \frac{Q_r}{2\sigma D_o T_o^4\left(1 + \frac{L}{R_o}\right)\eta_{act}^*} \tag{32}$$

The heat rejected by the tubes and fins Q_r can be related to the fraction of the total radiator heat rejected by the vapor header X_{VH}' according to

$$Q_r = Q_{rej}\left(1 - X_{VH}'\right) \tag{33}$$

Combining equations (31) to (33) then yields

$$A_t = \frac{\pi Q_{rej}\left(1 - X_{VH}'\right)}{2\sigma T_o^4\left(1 + \frac{L}{R_o}\right)\eta_{act}^*} \tag{34}$$

Accordingly, the outside area of the vapor header can be written in terms of its heat rejection rate as

$$A_{VH} = \frac{Q_{rej} X_{VH}'}{F_{VH}\sigma\epsilon T_2^4} \tag{35}$$

where F_{VH} is the geometric angle factor from the vapor header to space. A value of $F_{VH} = 0.85$ has been used in these programs. For simplicity, equation (35) assumes that the header surface emits at the same temperature as the vapor header inlet stagnation temperature. The small error involved in the header surface temperature will have a negligible effect on the radiator panel performance since the heat rejected from the header is only of the order of 5 percent of the total radiator heat rejection. Inserting equations (34) and (35) into equation (30) yields

$$A_v = \frac{Q_{rej}}{\sigma}\left[\frac{\pi(1 - X_{VH}')}{2T_o^4\left(1 + \frac{L}{R_o}\right)\eta_{act}^*} + \frac{X_{VH}'}{T_2^4 F_{VH}\epsilon}\right] \tag{36}$$

It is implied in equations (30) to (36) that the tubes and vapor header should be treated as an entity with regard to meteoroid protection. Therefore, the tubes and the vapor header are given the same protection (armor thickness).

Equations (29) and (36) are part of a set of equations that yields the wall thickness of the radiator tubes. Solution of these equations requires inputs of L/R_o, N_c, η_{act}^* from equation (26), total radiator heat rejection from the cycle analysis, and the fraction of the total heat rejected by the vapor header X'_{VH}. The value X'_{VH} is obtained from equations that determine the amount of heat rejected by the vapor header and are given in a later section of this report. The results consist of the armor thickness δ_a, vulnerable area A_v, and the tube outside temperature T_o.

Minimum Weight Program

Since the previous procedure generally requires a large number of calculations to determine a minimum weight radiator or a radiator of specific geometry (through the variation of N_c and L/R_o), a less exact analysis is developed that can be used for preliminary design purposes or for a parametric study of variables other than finned-tube geometry. This procedure produces a single radiator design that is approximately a minimum weight radiator configuration. The analysis cannot be used if a specific radiator area requirement or specific fin and tube dimensions are dictated by vehicle-radiator integration or construction.

The design of a radiator tube panel having a minimum weight per unit heat rejection follows the procedure given in reference 12. This method formulates the general expression for the total fin and tube heat rejection per unit weight, takes its first derivative with respect to fin length L and fin thickness t, sets the derivatives equal to zero, and combines the two expressions. The resultant equation describes the relation between the slope of the fin temperature profile at the fin base and the value of ϵN_c that will yield a minimum weight finned-tube radiator. Using these results along with the equation obtained from differentiating the equation for finned tube heat rejection per unit weight with respect to fin half length L and setting it equal to zero yields a cubic equation that provides the fin half-length for maximum Q_r/W_r for a given tube size and material. This equation is given as

$$\frac{8\rho_f \sigma \epsilon T_o^3}{k} L^3 + \frac{3\pi \rho_f \sigma \epsilon F_t T_o^3 (D_i + 2\delta_c + 2\delta_a)}{k F_f \eta_f} L^2 - \epsilon N_c \left[\rho_c \pi \delta_c (D_i + \delta_c) + \rho_t \pi \delta_a (D_i + 2\delta_c + \delta_a)\right] = 0 \qquad (37)$$

In addition to the overall assumptions previously mentioned, it is further assumed for equation (37) that

(1) The flat plate fin efficiency η_f is a constant (0.55) approximating conditions for a minimum weight fin. This fixed value is given by the expression $\eta_f = -\dot{\theta}/\epsilon N_c$ where the value of ϵN_c for maximum Q_r/W_r equals 0.90. The value of $\dot{\theta}$ is obtained from the solution of equation (19).

(2) The tube surface effect on the fin F_f is assumed constant at a value of 0.85 and independent of emissivity, N_c, or the L/R_o ratio (ref. 7).

(3) The radiator tube radiant interchange factor F_t is also assumed con-

stant at a value of 0.85 and is not affected by emissivity, N_c, or L/R_o (ref. 7).

(4) The emissivity ϵ is an arbitrary value and not affected by the finned-tube-cavity effect.

Once the fin length has been determined from equation (37), the remaining dimension that describes the fin geometry, its thickness, can be calculated from the relation

$$t = \frac{2\sigma\epsilon T_o^3 L^2}{k(\epsilon N_c)} \tag{38}$$

This approach optimizes only the fin and tube and does not take into account the vapor and liquid header that could have an influence on the optimum value of ϵN_c and the resultant finned-tube configuration. Equation (37) is based on the outside tube temperature and does not involve the inside tube temperature nor the resultant ΔT across the wall. Equation (27) is used to obtain this temperature drop in the same manner that was employed in the Parametric Program analysis.

The tube armor thickness δ_a is again obtained from equation (29), which requires inputs of meteoroid flux and density constants along with a description of the vulnerable area of the tubes and vapor header A_v. To obtain the expression for vulnerable area appropriate to the Minimum Weight Program, it is necessary to rewrite the heat-rejection equations for the tube and the fin by using the approximations and parameters of this program:

$$Q_t = \pi F_t D_o \epsilon \sigma T_o^4 NZ \tag{39}$$

and

$$Q_f = 4\eta_f F_f L \epsilon \sigma T_o^4 NZ \tag{40}$$

while the total heat rejected by the panel is given by

$$Q_r = Q_t + Q_f \tag{41}$$

Combining equations (39) to (41) yields

$$Q_r = \pi D_o NZ \left(\epsilon\sigma T_o^4 F_t + 4\eta_f F_f \frac{L}{\pi D_o} \epsilon\sigma T_o^4\right) \tag{42}$$

or

$$\pi D_o NZ = A_t = \frac{\pi D_o Q_r}{\epsilon\sigma T_o^4(\pi D_o F_t + 4\eta_f F_f L)} \tag{43}$$

Introducing $X_{tf}' = Q_r/Q_{rej}$ gives

$$A_t = \frac{\pi D_o X'_{tf} Q_{rej}}{\epsilon \sigma T_o^4 (\pi D_o F_t + 4\eta_f F_f L)} \tag{44}$$

The heat radiated by the vapor header is given by

$$Q_{VH} = \epsilon \sigma A_{VH} T_2^4 F_{VH} \tag{45}$$

or

$$A_{VH} = \frac{Q_{VH}}{\epsilon \sigma T_2^4 F_{VH}} \tag{46}$$

Adding equations (44) and (46) and expressing D_o in terms of inside diameter and liner and armor thickness gives the vulnerable area:

$$A_v = \frac{1}{\epsilon \sigma} \left\{ \frac{\pi (D_i + 2\delta_c + 2\delta_a) X'_{tf} Q_{rej}}{\left[\pi (D_i + 2\delta_c + 2\delta_a) F_t + 4\eta_f F_f L\right] T_o^4} + \frac{Q_{VH}}{F_{VH} T_2^4} \right\} \tag{47}$$

Equations (37), (38), and (47) require inputs of tube inside diameter, liner thickness, the fraction of the total heat rejected by the vapor header, the cycle requirements, and the values of the previously mentioned constants. The simultaneous solution of equations (27), (29), (37), (38), and (47) yields values of the parameters δ_a, t, L, T_o, and A_v.

HEADER DESIGN

After the fins have been designed by either of the two procedures just discussed, the computer program proceeds with the header design. The program was made sufficiently flexible and inclusive so as to be able to generate header designs for each of the configurations illustrated in figure 2. For all configurations, the vapor header is made up of one (in the case of the two-panel configuration) or two (in the case of the one- or four-panel configurations) symmetrical sections generated by a rotated parabola given by the equation

$$y^2 = 4bx \tag{48}$$

where the constant b describes the distance from the vertex of the parabola to its focal point as shown in figure 8. The parabolic shape results from the provision that the vapor velocity be constant throughout the vapor header length. The condensing tubes, in all configurations, are distributed evenly along the vapor header and end in liquid headers of constant diameter.

Header Surface Area

Vapor header. - The vapor header design was started by applying the general formula for the area of a paraboloid of revolution for the parabola described by equation (48). This expression (ref. 22, p. 148) is given in terms of the geometry of figure 8 as

$$\bar{S} = \frac{8}{3}\frac{\pi}{b}\left[(bx + b^2)^{3/2} - b^3\right] \tag{49}$$

where the factor x describes the running coordinate along the length of the paraboloid. Expanding equation (49) and neglecting terms that involve b^2 and b^3 give the surface area of the paraboloid:

$$\bar{S} = \frac{8}{3}\pi x(xb)^{1/2} \tag{50}$$

Equation (50), which is for a single paraboloid, can be rewritten in terms of the nomenclature of the configuration shown in figure 8. When $D = D_{VH}$,

$$x = \frac{m_1 Y}{2}$$

and

$$b = \frac{D_{VH}^2}{8m_1 Y}$$

The resultant equation, which is a general expression for the entire surface area for a single or multipanel vapor header, can be given as

$$A_{VH} = \frac{2}{3}\pi Y D_{VH} \tag{51}$$

The factors m_1, m_2, and m_3 are essential constants that describe the effect of the variation in the number of panels on the vapor header configuration. The factors m take on the following values for one-, two-, and four-panel configurations as shown in figure 2:

Panels	1	2	4
m_1	1	2	1
m_2	1	1/2	1/2
m_3	1	1	1/2

The quantity Y in equation (51) is defined as the physical length of the vapor header for each panel configuration and is given by the expression

$$Y = 2m_2N\left(L + \frac{1}{2} D_i + \delta_c + \delta_a\right) \tag{52}$$

The number of radiator tubes N in the previous equation is determined by using the following equation, which is an initial approximation based on flow continuity at the tube inlet:

$$N = \frac{4\dot{W}(QUAL*)}{\rho_g^* u_0 \pi D_i^2} \tag{53}$$

where the tube inlet vapor velocity u_0 is a variable that is iterated upon in the program. Even though the vapor quality in the header will be decreased along the header length due to the condensation and would vary at each individual radiator tube inlet, it is assumed for simplicity in this analysis that all the tubes will be at a constant inlet quality. The expression that relates the header inlet quality (QUAL2) and the inlet quality to the radiator tubes (QUAL*) is

$$QUAL* = QUAL2 - \frac{q_{VH}}{h} \tag{54}$$

Equation (54) depends on the heat rejected by the vapor header and can be obtained from the expression

$$3600\ \dot{W}q_{VH} = \epsilon\sigma T_2^4 A_{VH} F_{VH} \tag{55}$$

In terms of the maximum header diameter and physical length of the vapor header from equations (51) and (55), the vapor header heat rejection is given as

$$q_{VH} = 0.00058\ \epsilon\sigma \frac{T_2^4 Y D_{VH}}{\dot{W}} F_{VH} \tag{56}$$

The maximum diameter of the vapor header D_{VH} mentioned in the previous set of equations will be obtained from the vapor header pressure drop analysis in the next section.

<u>Liquid header</u>. - Inasmuch as the liquid header is generally quite small compared with the vapor header, the liquid header is assumed to have a constant diameter that is determined by applying the continuity equation at the header exit:

$$D_{LH} = \left(\frac{2m_3\dot{W}}{\pi\rho_L V_{LH}}\right)^{1/2} \tag{57}$$

The maximum fluid velocity at the header exit V_{LH} is assumed for calculation purposes to be 4 feet per second to minimize the pressure drop. The surface area of the liquid header is not included since its heat rejection to space is generally insignificant compared with that of the vapor header and finned-tube panel.

Vapor Header Pressure Drop

The pressure drop in the vapor header is obtained by integrating the basic Fanning equation

$$dP = -\frac{2f\rho_g u_{VH}^2}{gD}\,dx \tag{58}$$

where D is the local header diameter at any point (fig. 8) and the friction factor is calculated for simplicity by assuming one-phase turbulent flow. The relation for the friction factor is

$$f = \frac{0.046}{(Re_D)^{0.2}}$$

where Re_D is the local Reynolds number at any point on the header length and given as $Re_D = \frac{\rho_g u_{VH} D}{\mu_g}$. Furthermore the vapor header diameter at any position x can be obtained from equation (48) by using the definition of b and letting $y = D/2$. This relation is

$$D = D_{VH}\left(\frac{2x}{m_1 Y}\right)^{1/2} \tag{59}$$

The basic Fanning pressure drop equation can now be expressed as

$$dP = -\frac{0.092\ \rho_g u_{VH}^2}{(Re)^{0.2} g D_{VH}\left(\frac{2x}{m_1 Y}\right)^{0.6}}\,dx \tag{60}$$

where Re is the Reynolds number based on the maximum vapor header diameter and the vapor density ρ_g is assumed constant and evaluated as a function of the turbine outlet temperature T_2 and pressure P_2. Equation (60) can then be integrated between the limits $x = 0$ and $x = m_1 Y/2$ to yield the pressure drop that is then compared to the header inlet pressure P_2:

$$\left(\frac{\Delta P}{P_2}\right)_{VH} = \frac{0.00357\ \rho_g u_{VH}^2 m_1 Y}{P_2 (Re)^{0.2} D_{VH}} \tag{61}$$

Equation (61) can be rewritten and solved for the maximum diameter of the vapor header:

$$D_{VH} = \frac{0.00357\ \rho_g u_{VH}^2 m_1 Y}{P_2(Re)^{0.2}\left(\frac{\Delta P}{P_2}\right)_{VH}} \tag{62}$$

The maximum vapor header diameter can be determined for a given value of $\Delta P/P_2$ by the simultaneous solution of equation (62) and the following relation, which is based on flow continuity at the header inlet,

$$D_{VH} = \left(\frac{m_1 2\dot{W}(QUAL2)}{\rho_g \pi u_{VH}}\right)^{1/2} \tag{63}$$

Equation (63) can also be used to solve for the inlet velocity of the vapor header once the maximum header diameter is determined.

Liquid Header Pressure Drop

The liquid header was assumed to be of constant diameter throughout its length. The equation for the pressure drop is obtained by applying Fanning's equation (58) along with the previous definition of friction factor over the increment of length dx:

$$dP = \frac{-0.092\ \rho_L V^2}{g(Re_x)^{0.2} D_{LH}}\ dx \tag{64}$$

where the velocity of the liquid varies along the length of the header and is given at any point as

$$V = \frac{4\dot{W}m_3 x}{\rho_L \pi D_{LH}^2 Y m_1} \tag{65}$$

Substitution of equation (65) into (64) along with the Reynolds number rewritten in terms of the total weight flow and maximum liquid velocity at the header exit yields

$$dP = \frac{-\rho_L}{350} \frac{(2V_{LH})^2\ x^{1.8}}{D_{LH}(Ym_1)^{1.8}(2Re_L)^{0.2}}\ dx \tag{66}$$

Equation (66) can be integrated over the limits from $x = 0$ to $x = m_1 Y/2$ to obtain

$$\Delta P_{LH} = +\frac{0.00051\ \rho_L V_{LH}^2 m_1 Y}{(Re_L)^{0.2} D_{LH}} \tag{67}$$

where ΔP_{LH} is the pressure drop in the liquid header and Re_L is the Reynolds number corresponding to the maximum liquid velocity V_{LH}.

RADIATOR TUBE PRESSURE DROP AND LENGTH

The temperature-entropy diagram for the power-generation cycle has been redrawn in figure 9 to include the pressure losses in the radiator. Partial condensation of the working fluid in the vapor header results in an entropy decrease between states 2 and O. For simplicity, it is assumed that this condensation occurs at constant temperature. A drop in temperature occurs between the state points O and * due to the turning pressure loss between the header and the tube and to the increased fluid velocity in the tube. This pressure drop is assumed to occur at constant entropy. The wet vapor condenses completely between states * and L, with a decrease in temperature corresponding to the static pressure drop in the tube. State L represents the vapor-liquid interface in the tube. The liquid, still in the tube, is subcooled from L to 4', where the temperature difference between L and 4' is equal to the temperature difference between 3 and 4, which is assumed in the cycle calculations for subcooling (fig. 4).

In this section of the analysis, computation will be made of the required number and length of tubes commensurate with the assigned pressure drop in the tubes.

Header to Tube Turning Loss

The saturation temperature of the vapor at the condensing tube entrance T^* was computed from the difference between the stagnation pressure in the vapor header and the static pressure in the tube entrance. The stagnation pressure in the vapor header was considered constant for all the tubes, and the aforementioned pressure difference was assumed to come from turning the flow from the vapor header into the tubes and an increase in flow velocity in the tubes. References 23 and 24 were used to obtain the relation between this pressure difference and the velocities in the vapor header and tubes. Figure 10 shows a plot of the ratio of the pressure difference (header stagnation minus tube static) to the dynamic head at the tube inlet K_H against the ratio of the velocity at the tube inlet to the header velocity u_O/u_{VH}. Data are shown for all airflow, a 0.86 quality air-water mixture, both with entrance radii of 0.1 inch; and three curves for all-water flow with entrance radii of 0.0625, 0.125, and 0.375 inch. It is seen from the curves for water that increasing the entrance radius decreases the value of K_H. The trend exhibited for water flow is assumed to hold for air or the 0.86 quality air-water mixture.

The difference between the stagnation pressure in the header and the static pressure in the tube entrance can be obtained from the relation

$$\Delta P = \frac{1}{2} K_H \rho_g \frac{u_O^2}{g} \tag{68}$$

in which the density ρ_g used in the expression for dynamic head in the tube has been computed for simplicity from the stagnation pressure and temperature in the header and the equivalent gas constant previously defined. The difference between the stagnation temperature in the header and the saturation temperature in the tube inlet can then be calculated from Clapeyron's relation, which holds for a vapor near saturation. The relation states that for a small change in T

$$\Delta P = Jh\rho_g \frac{\Delta T}{T} \tag{69}$$

if the specific volume of the liquid is small compared with that of the vapor. Combining equations (68) and (69) yields the expression

$$\Delta T = T_O - T^* = \frac{\frac{1}{2} K_H u_O^2 T_O}{Jhg} \tag{70}$$

Since the heat transferred across the condensate film on the tube inner wall is proportional to the product of the condensing heat-transfer coefficient and the difference between saturation temperature and the tube inside wall temperature, the inside wall temperature will be nearly equal to the saturation temperature T^* for the radiators considered herein, provided the condensing heat-transfer coefficient is high, for example, of the order of 10,000 Btu per hour per square foot per $^{\circ}F$. In these calculations, for simplicity, the tube inside wall temperature was taken equal to T^* as obtained from equation (70).

Initially, an estimate for u_O is supplied by the program. After the pressure drop in the tubes is obtained, a new value of u_O is computed to cause the calculated pressure drop to approach its assigned value. This iterative procedure is controlled by the subroutine GUIDE.

Tube Pressure Drop and Condensation Length

The length of the radiator tube required for condensation and the pressure drop across it are determined simultaneously by developing an incremental pressure drop over a small increment of tube length, and then performing a step-by-step numerical integration over the entire length of the tube. An energy balance for a small length of tube in which a two-phase fluid is flowing can be written by equating the heat released by the condensation of a small amount of vapor $h\ dw_L$ to the sum of the heat energy radiated, the energy involved in the change of sensible heat, and the energy required to change the kinetic energy of the fluid. Consider a section of the finned tube illustrated in figure 11 with the mass flows, enthalpies, and velocities as indicated at either end of the section. The quantity $\bar{q}$ represents the heat radiated per unit length of finned tube. The energy balance for the element dx is

$$\begin{aligned} w_L h_L + w_g h_g + \frac{1}{2gJ}\left(w_L V^2 + w_g u^2\right) &= \bar{q}\,dx + (w_L + dw_L)\left[h_L + (c_p)_L\,dT\right] + (w_g + dw_g)\left[h_g + (c_p)_g\,dT\right] \\ &+ \frac{1}{2gJ}(w_L + dw_L)(V^2 + 2V\,dV + dV\,dV) + \frac{1}{2gJ}(w_g + dw_g)(u^2 + 2u\,du + du\,du) \end{aligned} \tag{71}$$

where h_L and h_g are the enthalpies of the liquid and vapor, respectively.

If the second-order differentials are eliminated

$$\bar{q}\ dx + \left[w_L(c_p)_L + w_g(c_p)_g\right] dT - (h_g - h_L)\ dw_L$$

$$+ \frac{(V^2 - u^2)}{2gJ}\ dw_L + \frac{Vw_L\ dV + uw_g\ du}{gJ} = 0 \qquad (72)$$

Since the heat of condensation $h = h_g - h_L$,

$$h\ dw_L = \bar{q}\ dx - \frac{u^2 - V^2}{2gJ}\ dw_L + \left[(c_p)_L\ dT + \frac{V\ dV}{gJ}\right] w_L + \left[(c_p)_g\ dT + \frac{u\ du}{gJ}\right] w_g \qquad (73)$$

Because $\bar{q} = K\epsilon\sigma\pi D_i T_o^4/3600$, the energy equation (73) can be written as

$$h\ dw_L = \frac{K\epsilon\sigma\pi D_i T_o^4}{3600}\ dx + \left[(c_p)_L\ dT + \frac{V\ dV}{Jg}\right] w_L$$

$$- \left(\frac{u^2 - V^2}{2gJ}\right) dw_L + \left[(c_p)_g\ dT + \frac{u\ du}{Jg}\right] w_g \qquad (74)$$

By the Clausius-Clapeyron equation

$$dT = \frac{T}{Jh\rho_g}\ dP \qquad (75)$$

the energy balance can be transformed into

$$\frac{-K\epsilon\sigma\pi D_i T_o^4\ dx}{3600} = -h\ dw_L - \frac{u^2 - V^2}{2Jg}\ dw_L + \frac{w_L V\ dV + (w - w_L) u\ du}{Jg}$$

$$+ \left[(c_p)_L w_L + (c_p)_g (w - w_L)\right] \frac{T\ dP}{Jh\rho_g} \qquad (76)$$

If the velocity differentials and the pressure differential can be eliminated, the result will give a relation between the length differential and the formation of the condensate.

From the continuity equations for the liquid and the vapor, with the assumption that the densities are constant within the incremental tube length, the differential velocities are

$$\frac{dV}{V} = \frac{dw_L}{w_L} - \frac{dR_L'}{R_L'} \qquad (77)$$

and

$$\frac{du}{u} = \frac{dw_g}{w_g} - \frac{dR_g'}{R_g'} \tag{78}$$

where R_L' and R_g' are the fraction of the tube flow area A occupied by the liquid and the vapor, respectively. But

$$\left.\begin{aligned} R_L' + R_g' &= 1 \qquad & dR_L' + dR_g' &= 0 \\ w_L + w_g &= w \qquad & dw_L + dw_g &= dw = 0 \end{aligned}\right\} \tag{79}$$

so that equation (78) can be rewritten in terms of the liquid parameters

$$\frac{du}{u} = \frac{dR_L'}{1 - R_L'} - \frac{dw_L}{w - w_L} \tag{80}$$

The differential area fractions can be eliminated by recourse to the correlation of Lockhart and Martinelli (ref. 25). The reference shows that $R_L' = R_L'(X)$, where the correlating parameter in the turbulent-turbulent regime is given by

$$X^2 = \left(\frac{w_L}{w - w_L}\right)^{1.8} \frac{\rho_g}{\rho_L} \left(\frac{\mu_L}{\mu_g}\right)^{0.2} \tag{81}$$

The turbulent-turbulent regime was assumed for this analysis when it was discovered that, for radiator designs near minimum weight, both the vapor and the liquid velocities were high enough throughout most of the tube length to make this the predominant regime.

If it is assumed that the principal variation in X^2 is due to a change in w_L, the differential of X^2 is given by

$$2X\,dX = 1.8\left(\frac{w_L}{w - w_L}\right)^{0.8} \frac{(w - w_L) + w_L}{(w - w_L)^2} \left(\frac{\rho_g}{\rho_L}\right)\left(\frac{\mu_L}{\mu_g}\right)^{0.2} dw_L \tag{82}$$

and

$$\frac{dX}{dw_L} = \frac{0.9\ wX}{w_g w_L} \tag{83}$$

Then

$$dR_L' = \frac{dR_L'}{dX}\frac{dX}{dw_L}\,dw_L = 0.9\left(\frac{dR_L'}{dX}\right)\frac{wX}{w_g w_L}\,dw_L \tag{84}$$

The functional relation between R_L' and X, shown in figure 1 of reference 25, was stored in the computer by representing $\log R_L'$ as a polynomial function of $\log X$. The derivative dR_L'/dX was computed numerically from this representation.

Equations (77) and (80) now become

$$\frac{dV}{V} = \frac{dw_L}{w_L}\left(1 - 0.9\,\frac{dR_L'}{dX}\,\frac{X}{R_L'}\,\frac{w}{w_g}\right) \tag{85}$$

and

$$\frac{du}{u} = \frac{-dw_L}{w_g}\left(1 - 0.9\,\frac{dR_L'}{dX}\,\frac{X}{R_g'}\,\frac{w}{w_L}\right) \tag{86}$$

These expressions for the velocity differentials can be substituted into the energy equation (74) to give

$$h\,dw_L = \frac{K\epsilon\sigma\pi D_i T_0^4}{3600}\,dx + \frac{V^2\,dw_L}{Jg}\left(1 - 0.9\,\frac{dR_L'}{dX}\,\frac{X}{R_L'}\,\frac{w}{w_g}\right) - \frac{u^2\,dw_L}{Jg}\left(1 - 0.9\,\frac{dR_L'}{dX}\,\frac{X}{R_g'}\,\frac{w}{w_L}\right)$$

$$- \frac{(u^2 - V^2)}{2Jg}\,dw_L + \left[(c_p)_L w_L + (c_p)_g w_g\right]\frac{T\,dP}{Jh\rho_g} \tag{87}$$

which involves dP, dx, and dw_L only. The pressure differential can be broken down into a friction and momentum component

$$dP = dP_F + dP_m \tag{88}$$

The friction pressure loss per unit length was computed from the Lockhart-Martinelli correlation (ref. 25)

$$\left(\frac{dP}{dx}\right)_F = \Phi_g^2\left(\frac{dP}{dx}\right)_g \tag{89}$$

where $\Phi = \Phi(X)$ and $(dP/dx)_g$ is the friction pressure drop if the vapor flowed alone in the tube and is given as

$$\left(\frac{dP}{dx}\right)_g = -2f_g\,\frac{\overline{u}^2\rho_g}{gD_i} \tag{90}$$

where $\overline{u} = 4w_g/\pi D_i^2\rho_g$, and $f_g = 0.046/(Re_{gp})^{0.2}$ for turbulent flow. Also

$$Re_{gp} \equiv \frac{4w_g}{\pi D_i \mu_g} \tag{91}$$

and

$$\left(\frac{dP}{dx}\right)_F = -\Phi_g^2 \frac{0.092\ \mu_g^2}{gD_i^3\rho_g} (Re_{gp})^{1.8} \tag{92}$$

The differential change in pressure caused by a momentum change in the two-phase flow can be expressed as

$$-dP_m = \frac{1}{gA}\, d(\rho_L A R_L' V^2 + \rho_g A R_g' u^2) \tag{93}$$

By using the expressions previously derived for the derivatives and assuming the densities to be constant in the interval dx,

$$\frac{-dP_m}{dw_L} = \frac{\rho_L V^2 R_L'}{g w_L}\left(2 - \frac{dR_L'}{dX}\frac{0.9\ wX}{w_g R_L'}\right) - \left(\frac{\rho_g u^2 R_g'}{g w_g}\right)\left(2 - \frac{dR_L'}{dX}\frac{0.9\ wX}{w_L R_g'}\right) \tag{94}$$

and

$$dP = \frac{dP_m}{dw_L}\, dw_L + \left(\frac{dP}{dx}\right)_F dx \tag{95}$$

When the pressure differential is eliminated, the final form of the energy equation is

$$\left\{h - \frac{V^2}{Jg}\left(1 - \frac{0.9\ X}{R_L'}\frac{w}{w_g}\frac{dR_L'}{dX}\right) + \frac{u^2}{Jg}\left(1 - \frac{0.9\ X}{R_g'}\frac{w}{w_L}\frac{dR_L'}{dX}\right) - \left[(c_p)_L w_L + (c_p)_g w_g\right]\frac{T}{Jh\rho_g}\frac{dP_m}{dw_L}\right.$$

$$\left. + \frac{u^2 - V^2}{2Jg}\right\} dw_L = \left\{\frac{K\epsilon\sigma\pi D_i T_o^4}{3600} + \left[(c_p)_L w_L + (c_p)_g w_g\right]\frac{T}{Jh\rho_g}\left(\frac{dP}{dx}\right)_F\right\} dx \tag{96}$$

This equation is used in the following manner to find the length of the tube required for condensation L_c. The equation is solved for dx and numerically integrated until the vapor mass flow w_g is reduced to zero. The integrated value of x obtained when $w_g = 0$ is then denoted as L_c. In the process of numerically integrating equation (96), the pressure drop equation (eq. (95)) is also integrated to give the total change in pressure over the condensing tube length.

To start the numerical integration of equations (95) and (96), it is necessary to have the initial values of all quantities involved corresponding to conditions at the tube inlet where $x = 0$. The mass flow per tube is constant for the entire tube length and can be obtained from

$$w = \frac{\dot{W}}{N}$$

where

$$N = \frac{4\dot{W}\ QUAL^*}{\pi \rho_g^* u_0 D_i^2} \tag{97}$$

In the foregoing equation $\dot{W}$ was calculated from equation (7), QUAL* was calculated from equation (54), and D_i is part of the input data. The initial vapor density at the tube inlet is given by

$$\rho_g^* = \frac{P^*}{RT^*} \tag{98}$$

and the vapor velocity at the tube inlet is assigned by the subroutine GUIDE as described in the APPROACH section of this report. Initial values for some of the variables then are obtained as follows:

$$w_g = w\ QUAL^* \qquad \text{and} \qquad w_L = w - w_g \tag{99}$$

Initial values of X can be calculated from equation (81) after which the curve fit, built into the program, can determine the corresponding value of R_L'. Equation (79) is used to obtain R_g'. The initial value of the liquid velocity is given by

$$V_0 = \frac{4w_L}{\pi \rho_L R_L' D_i^2} \tag{100}$$

Subcooler Length

In addition to the tube length L_c required to condense the fluid, the tube must have additional length sufficient to subcool the liquid to a predetermined value. The heat-transfer equations for the subcooler are

$$-K\epsilon\sigma\pi D_i T_o^4 = h_{sc}(T_o - T_L)\pi D_i = 3600(c_p)_L w \frac{dT_L}{dx} \tag{101}$$

The differential of the first two equalities in equation (101) yields

$$dT_L = \left(1 + \frac{4K\epsilon\sigma T_o^3}{h_{sc}}\right) dT_o \tag{102}$$

Substituting equation (102) into equation (101) gives

$$-dx = \frac{3600(c_p)_L w}{K\epsilon\sigma\pi D_i T_o^4} \left(1 + \frac{4K\epsilon\sigma T_o^3}{h_{sc}}\right) dT_o \tag{103}$$

If the temperature difference between the outside tube wall and the liquid is assumed negligible, then equation (103) can be integrated to give the subcooler length in terms of the temperatures at either end of the subcooler:

$$L_{sc} = \frac{1200(c_p)_L w}{K\pi D_i}\left\{\left[\frac{1}{(T_L - \Delta T_{sc})^3} - \frac{1}{T_L^3}\right]\frac{1}{\epsilon\sigma} + \frac{12K}{h_{sc}} \ln \frac{T_L}{T_4'}\right\} \tag{104}$$

Because of the high heat-transfer coefficient of a liquid metal h_{sc}, the second term in equation (104) is small compared with the first and was neglected in this analysis. The programed form of the equation for subcooler length is

$$L_{sc} = \frac{300(c_p)_L G D_i}{K\epsilon\sigma}\left[\frac{1}{(T_L - \Delta T_{sc})^3} - \frac{1}{T_L^3}\right] \tag{105}$$

where $G = w/A = 4w/\pi D_i^2$.

The total radiator tube length Z was the combined length of the condensing portion and the subcooler portion, that is

$$Z = L_c + L_{sc} \tag{106}$$

RADIATOR WEIGHT AND GEOMETRY

With the calculation of the output parameters from the cycle, finned-tube geometry, header, and pressure drop sections, the radiator weight and planform area can be determined for both the Parametric and Minimum Weight Programs. The weights of the various radiator components are given by the following expressions:

Vapor header weight:

$$W_{VH} = \frac{2}{3}\pi\left\{\left[D_{VH} + (\delta_{VH})_c\right]\left[Y + (\delta_{VH})_c\right](\delta_{VH})_c\rho_c + \left[D_{VH} + 2(\delta_{VH})_c + \delta_a\right]\left[Y + 2(\delta_{VH})_c + \delta_a\right]\delta_a\rho_t\right\} \tag{107}$$

Liquid header weight:

$$W_{LH} = \frac{\pi}{m_2} Y\left\{\frac{\rho_L D_{LH}^2}{4} + \rho_c(\delta_{LH})_c\left[D_{LH} + (\delta_{LH})_c\right] + \rho_t\delta_a\left[D_{LH} + \delta_a + 2(\delta_{LH})_c\right]\right\} \tag{108}$$

The fin and tube panel weight can be calculated by using the expression

$$W_r = NZ\left\{\frac{4\rho_f\sigma R_o^3 T_o^3}{kN_c}\left(\frac{L}{R_o}\right)^3 + \pi\left[\rho_c\delta_c(D_i + \delta_c) + \rho_t\delta_a(D_i + 2\delta_c + \delta_a)\right]\right\} \tag{109}$$

The total radiator weight is then obtained by summing the results of the individual contributions as

$$W = W_{VH} + W_{LH} + W_r \tag{110}$$

The various inputs required to obtain solutions for the previous equations describing radiator weight are obtained by using the results of the optimization program plus input values of tube inside diameter and material properties.

The total heat rejected by the radiator, which is an output of the cycle program, is divided by the total radiator weight obtained from equation (110) to form the heat rejected per unit weight Q_{rej}/W. For the Parametric Program the maximum heat rejected per unit weight is a function of the ratio L/R_o and conductance parameter N_c. A typical plot of Q_{rej}/W is shown for a specific example in figure 12.

In addition to radiator panel weight, it is also of considerable interest to obtain the required planform area of the radiator panel. Radiator planform area A_p is given by the expression

$$A_p = 2NZ(R_i + \delta_c + \delta_a)\left(1 + \frac{L}{R_o}\right) \tag{111}$$

Thus, planform area will vary directly with the total tube length NZ and will also be a function of the ratio L/R_o. Results for planform area A_p are obtained by using inputs of tube inside radius and the ratio L/R_o along with values of N, Z, and δ_a obtained from the simultaneous solution of the equations describing heat transfer, meteoroid protection, and pressure drop.

Additional factors that describe the radiator geometry, which can be obtained by using the results of the optimization programs, are the panel aspect ratio (panel width divided by the individual tube length) W'/Z, fin thickness t, and fin length L.

APPLICATION TO OTHER FINNED-TUBE CONFIGURATIONS

The Parametric Program can be used to analyze finned-tube configurations other than the central finned tube by making appropriate changes in the SUBW subroutine. For each configuration a unique heat-transfer analysis with its attendant view factors and overall efficiency is required. A change in finned-tube configuration may also entail a change in the computation of the tube vulnerable area. The weight computations are also unique for each configuration.

Several finned-tube configurations have been analyzed in reference 13. These include, in addition to the central finned tube, the open sandwich fin tube (with and without fillet), and the closed sandwich fin tube with variable side wall thickness. Formulas for view factors, overall efficiency, vulnerable area, and panel weight for each of the aforementioned configurations are given in reference 13.

RESULTS

Calculations that use the resultant equations developed in the analysis for the Parametric Program and the Minimum Weight Program require inputs such as tube inside diameter, radiator temperature, power level, cycle conditions, material considerations, meteoroid protection criteria, and tube and header pressure drop to specify a system completely. For this reason, weight optimizations and area determinations can only be made for specific cases. To show sample results and compare the two programs on a basis of heat rejection per unit weight and radiator geometry, a single power level and cycle were chosen. The power level was kept at 1 megawatt with potassium chosen as the cycle fluid. A maximum cycle temperature of 2460° R and a radiator temperature of 1700° R were used. It was also specified that the radiator tubes would subcool the condensate 100°. Additional cycle requirements such as turbine and generator efficiencies were set at 0.75 and 0.90, respectively, with 10 percent of the generator output required for accessories and controls. The emissivity of the coating on the fins, tubes, and headers was taken to be 0.90, and the space effective sink temperature was assumed to be 0° R. The tubes and headers were arranged in the four-panel configuration shown in figure 2.

Materials specified for the radiator include tube liners made of columbium alloy and tube armor and fins made of beryllium. Radiator tube inside diameters from 0.375 to 1.125 inches were used in the calculations with tube pressure drop ratio $\Delta P/P^*$ set at 5 percent. The vapor header pressure drop ratio was set at 2 percent with the turning loss coefficient K_H equal to 1.15. The liquid header was designed with a maximum exit velocity of 4 feet per second.

Meteoroid protection thickness calculations assumed a survival probability of 0.995 with a 500-day mission time and an occlusion factor of unity. The meteoroid density and population parameters used were those given in the analysis section.

Using the prescribed inputs alone with the programed equations of the two programs enabled calculations and comparisons to be made of the results.

Parametric Program

Results that show the variation in heat rejection rate per unit weight as a function of the ratio L/R_o for several values of conductance parameter N_c are plotted in figure 12 for the 1-inch inside tube diameter. Each constant N_c curve is seen to peak at a specific value of the ratio L/R_o. The locus of the maximums of figure 12 is plotted in figure 13, together with the corresponding values for the other three diameters. In general, the family of maximum Q_{rej}/W can be represented by the envelope curve around the individual curves in figure 12, or by a single curve through the maximum of each constant N_c curve. For this particular analysis, the latter curve was chosen because there was less uncertainty in the selection of the individual maximums than in the determination of the tangents for the envelope curve.

It is seen from figure 13 that the maximum Q_{rej}/W occurs at an N_c in the range from 0.5 to 1.0 depending on the choice of tube inside diameter. At a tube inside diameter of 0.625, which yields minimum weight, the optimum conductance parameter N_c obtained is approximately 0.65. The corresponding value of the ratio L/R_o obtained for a maximum Q_{rej}/W of 3090 Btu per hour per pound was 2.00 for the 0.625-inch tube inside diameter. It can be seen from figure 13, however, that N_c can vary from 0.5 to 1.5 and produce only 3 percent variation in the specific-heat-rejection rate.

For high power level systems that result in large radiators, the weight of the vapor and liquid headers can be a significant portion of the total radiator weight. Figure 14 shows sample results of the ratio of the vapor plus liquid header weights to the overall radiator weight for the conditions of maximum heat rejection per unit weight. At maximum Q_{rej}/W, which occurs approximately at a tube inside diameter of 0.625 inch and a conductance parameter of 0.65, the combined header weights accounted for approximately 23 percent of the total radiator weight.

The radiator planform area plotted in figure 15 against the ratio L/R_o for various values of N_c and inside tube diameter is obtained for the peak condition of Q_{rej}/W shown in figure 13. The total variation of planform area with tube inside diameter for a specific value of the ratio L/R_o is less than 4 percent.

An additional factor of interest with respect to the geometry of the radiator is the panel aspect ratio, which is defined as the ratio of panel width W' to tube length Z. Figure 16 is a plot of aspect ratio W'/Z against the ratio L/R_o for the four tube diameters investigated. This set of curves is for a four-panel radiator chosen for the analysis. The aspect ratio of a panel increases if one or all of the following variables change: (1) the ratio L/R_o increases, (2) the conductance parameter N_c increases, or (3) the inside tube diameter decreases. The aspect ratio for minimum weight was about 2.40.

Total fin thickness plotted in figure 17 against the ratio L/R_o for peak Q_{rej}/W decreases with decreasing tube diameter or increasing N_c. For the tube inside diameters chosen, the values of fin thickness obtained are all of reasonable fabricational magnitude. The fin thickness obtained for minimum weight conditions is 0.103 inch.

Comparison of Parametric and Minimum Weight Programs

It has already been stated that the conductance parameter N_c for the maximum specific-heat-rejection rate Q_{rej}/W in the Parametric Program is about 0.65. This value although less than that used in the Minimum Weight Program (1.0) has a minor effect on the optimum values of weight and geometry obtained for the central finned-tube radiator. Comparisons of the values of two parameters L/R_o and D_i yielding maximum Q_{rej}/W for the two programs are shown plotted in figures 18 and 19. In figure 18 the specific-heat-rejection rate in Btu per hour per pound is plotted against tube inside diameter for both programs. The curve for the Parametric Program results in a value of Q_{rej}/W essentially the same as that obtained for the Minimum Weight Program at near optimum conditions. The curves for both programs reach a maximum at an inside diameter of about 0.625 inch.

In figure 19, the ratio L/R_o for maximum Q_{rej}/W is plotted against tube inside diameter for the Parametric Program. Also shown is a curve based on a constant value of $N_c = 1$ for the Minimum Weight Program. A comparison of the curves indicates that the ratio L/R_o obtained from the Parametric Program increases with increasing tube inside diameter, whereas the ratio L/R_o decreases with increasing tube diameter for the Minimum Weight Program.

Comparison of the resultant radiator geometries also indicates good agreement as shown by the planform area, panel aspect ratio, and fin thickness curves presented in figures 20, 21, and 22, respectively. At small diameters the discrepancy in planform area between the two programs increases somewhat due, in part, to the simplifying assumptions required in the Minimum Weight Program, such as constant ϵN_c and constant values of fin and tube thermal effectiveness. The panel aspect ratio for the four-panel radiator used in this analysis showed practically no difference between the two programs, as indicated in figure 21. The comparison of the fin thickness obtained for the two programs shown in figure 22 indicates an increasing fin thickness with increasing tube inside diameter for both programs. Curves are given for fin thickness at maximum Q_{rej}/W for the Parametric Program and at $N_c = 1$ for the Minimum Weight Program. Smaller values of t obtained from the Minimum Weight Program are approximately 12 percent less than those obtained by using the Parametric Program.

Comparison of the results of the Parametric and Minimum Weight Programs justifies the use of the Minimum Weight Program for general radiator weight optimization studies because of its relative speed, simplicity, and accuracy, providing it is not necessary to specify the ratio L/R_o. The Parametric Program is most useful in designing radiators that must satisfy configuration limitations and radiator-vehicle integration requirements. Since the Parametric Program requires a variation in N_c and L/R_o to obtain the peak Q_{rej}/W, and the computer running time for a single choice of N_c and L/R_o is approximately that for a complete optimum design by the Minimum Weight Program, the total running time of the Parametric Program will far exceed that of the Minimum Weight Program.

CONCLUDING REMARKS

The investigation reported herein has considered the design of direct condensing central finned-tube space radiators that meet minimum weight and vehicle integration requirements. Two electronic digital computer programs were developed, one of which is based on a fixed conductance parameter, and the other on a variable conductance parameter and a variable fin-half-length to tube-outside-radius ratio. It has been shown that, for the 1 megawatt, high-temperature Rankine system chosen for the comparison, the two programs agreed closely when compared on a weight and geometry basis. The calculated results obtained substantiated the fact that the value of the product of the conductance parameter and the apparent emissivity for maximum heat rejection per unit weight, as determined by the Parametric Program, although different from that used in the Minimum Weight Program resulted in radiator weights that were essentially the same at conditions of maximum heat rejection per unit weight. Radiator planform area and panel aspect ratio were also investigated and showed very close agreement.

These conclusions justify the use of the Minimum Weight Program for general radiator optimization studies, since it is relatively fast, and the use of the Parametric Program for the design of radiators that must satisfy configuration limitations and radiator-vehicle integration requirements.

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, June 30, 1964

APPENDIX A

ANALYTICAL RELATIONS FOR THERMODYNAMIC PROPERTIES OF WORKING FLUIDS

The enthalpy H and entropy S of the working fluids on the vapor and liquid portions of the vapor dome, required for the program cycle calculations, were taken from reference 15. The values for potassium vapor agreed within 2 percent with the values given in reference 17 over a range of temperatures between 1400° and 2000° R. Both liquid and vapor enthalpies and entropies were expressed as polynomial functions of temperature for four different working fluids. The maximum error between the curve fits and the values of reference 15 was less than 0.2 percent for any temperature between 700° and 2700° R. The polynomial representations are as follows:

Potassium:

$$H_L = -10.916 + 0.22663\ T - 3.1879\times10^{-5}\ T^2 + 7.6005\times10^{-9}\ T^3$$

$$S_L = 0.20136 + 5.8031\times10^{-4}\ T - 3.1184\times10^{-7}\ T^2 + 9.0984\times10^{-11}\ T^3 - 1.0291\times10^{-14}\ T^4$$

$$H_g = 961.89 + 0.21716\ T - 6.9939\times10^{-5}\ T^2 - 1.1790\times10^{-8}\ T^3$$

$$S_g = 4.5497 - 7.1959\times10^{-3}\ T + 6.6733\times10^{-6}\ T^2 - 3.2936\times10^{-9}\ T^3 + 8.2908\times10^{-13}\ T^4 - 8.3530\times10^{-17}\ T^5$$

Sodium:

$$H_L = -29.978 + 0.38999\ T - 5.5568\times10^{-5}\ T^2 + 1.1421\times10^{-8}\ T^3$$

$$S_L = 0.12431 + 1.2843\times10^{-3}\ T - 9.3433\times10^{-7}\ T^2 + 4.1314\times10^{-10}\ T^3 - 9.6735\times10^{-14}\ T^4 + 9.3008\times10^{-18}\ T^5$$

$$H_g = 1863.5 + 0.73505\ T - 5.0819\times10^{-4}\ T^2 + 1.5944\times10^{-7}\ T^3 - 1.6987\times10^{-11}\ T^4$$

$$S_g = 8.9462 - 1.4218\times10^{-2}\ T + 1.2793\times10^{-5}\ T^2 - 6.1917\times10^{-9}\ T^3 + 1.5385\times10^{-12}\ T^4 - 1.5359\times10^{-16}\ T^5$$

Rubidium:

$$H_L = 2.4884 + 0.0877\ T$$

$$S_L = 0.11715 + 3.0833\times10^{-4}\ T - 2.0709\times10^{-7}\ T^2 + 8.8713\times10^{-11}\ T^3 - 2.0508\times10^{-14}\ T^4 + 1.9470\times10^{-18}\ T^5$$

$$H_g = 396.74 + 0.12658\ T - 6.6081\times10^{-5}\ T^2 + 2.0043\times10^{-8}\ T^3 - 2.0383\times10^{-12}\ T^4$$

$$S_g = 1.9173 - 2.8787\times10^{-3}\ T + 2.6242\times10^{-6}\ T^2 - 1.2748\times10^{-9}\ T^3 + 3.1688\times10^{-13}\ T^4 - 3.1607\times10^{-17}\ T^5$$

Cesium:

$$H_L = 1.4243 + 0.057200\ T$$

$$S_L = 0.085532 + 2.1038\times10^{-4}\ T - 1.4709\times10^{-7}\ T^2 + 6.5234\times10^{-11}\ T^3 - 1.5531\times10^{-14}\ T^4 + 1.5117\times10^{-18}\ T^5$$

$$H_g = 241.30 + 8.9768\times10^{-2}\ T - 5.3090\times10^{-5}\ T^2 + 1.7747\times10^{-8}\ T^3 - 2.0381\times10^{-12}\ T^4$$

$$S_g = 1.1868 - 1.7305\times10^{-3}\ T + 1.5653\times10^{-6}\ T^2 - 7.5471\times10^{-10}\ T^3 + 1.8648\times10^{-13}\ T^4 - 1.8517\times10^{-17}\ T^5$$

APPENDIX B

COMPUTER PRINTOUT SHEET

Printout sheets from the electronic digital computer are included as a part of this appendix. The sheets are typical of a single run with the Minimum Weight and Parametric Programs. They show both the inputs and outputs.

The first group of figures after the run title are the inputs for the power cycle and the selected pressure drops. A brief explanation of these inputs follows:

T1 turbine inlet temperature, ^{o}R

T2 radiator temperature, ^{o}R

DTSC amount that liquid is subcooled in radiator

ETAT turbine efficiency

ETAG generator efficiency

QP heat lost between boiler and turbine, Btu/lb

DP/PVH fractional pressure drop in vapor header

DP/P* fractional pressure drop in tubes

PE electrical power output available, kw

KP ratio between available electrical power output and generator output

VLH maximum velocity in liquid header, ft/sec

PANELS arrangement of tubes with respect to headers (fig. 2)

The second group of inputs are some of the parameters associated with the meteoroid protection equation:

ALPHA number of particles with mass of 1 gram or greater hitting area of 1 square foot per day (ref. 18)

BETA negative of slope of cumulative frequency against minimum mass when expressed on log-log plot

A LIL spalling factor

RHO P meteoroid density, g/cc

VBAR average meteoroid velocity, ft/sec

The following miscellaneous quantities must also be supplied:

KH vapor header to tube turning loss factor (see fig. 10)

FBAR occlusion factor

KF thermal conductivity of fin, Btu/(ft)(hr)($^{\circ}$F)

KT thermal conductivity of armor, Btu/(ft)(hr)($^{\circ}$F)

RHOT density of armor, lb/cu ft

RHOF density of fin, lb/cu ft

RHOC density of liner, lb/cu ft

ET Young's modulus of armor material, lb/sq ft

N number of N penetrations

P(N) probability of N penetrations

TAU mission time, days

DELCVH thickness of liner in vapor header, ft

The last group of inputs is concerned with the properties of the working fluid:

MU L viscosity of liquid phase, lb/(ft)(sec)

MU G viscosity of vapor phase, lb/(ft)(sec)

RHOL liquid density, lb/cu ft

P2 saturation pressure corresponding to radiator temperature, lb/sq ft

CP G specific heat of vapor, Btu/(lb)($^{\circ}$F)

CP L specific heat of liquid, Btu/(lb)($^{\circ}$F)

The results of the power cycle calculations are independent of the tube diameter. They appear as the first part of the output:

WBAR ideal cycle work output (eq. (8)), Btu/lb

QUAL2 quality at turbine exhaust (eq. (12))

QIN heat supplied to cycle (eq. (2)), Btu/hr

ETHERM thermal efficiency (eq. (15))

WDOT power cycle mass-flow rate (eq. (7)), lb/sec

ETAC cycle efficiency (eq. (16))

T2/T1 turbine temperature ratio

H heat of condensation $H_2'' - H_3$, Btu/lb

RHOG vapor density, lb/cu ft

Additional inputs for the Parametric Program are

FVH vapor header view factor to space

TST program convergence testing factor

BJBA4 number of tube diameters

FMES mesh size for solution of equation (19)

TST1 convergence testing factor for equation (19)

TABETA overall efficiency table or equation (25) branch

FLR ratio of fin half-length to tube outer radius, L/R_o

FNC conductance parameter, N_c

There follow four sets of data of four lines each. The corresponding lines in each set of data are for radiators with tube inside diameters in inches as indicated by the column DI IN. The fin half-length L IN. and thickness T SML IN. are given in inches, as are the armor thickness DELTA IN. and the liner thickness DELC IN. The radiation multiplier K is defined in the section SYMBOLS. Other calculated results in the first set are:

TEMP 0 surface temperature at tube inlet, $^{\circ}$R

RHOG* vapor density at tube inlet (eq. (98)), lb/cu ft

N number of radiator tubes (eq. (53))

DVH maximum diameter of vapor header (eq. (63)), ft

The second set of outputs consists of:

DLH diameter of liquid header (eq. (57)), ft

WVH weight of vapor header (eq. (107)), lb

WLH weight of liquid header (eq. (108)), lb

WR/PE specific weight of radiator panel, lb/kw

Y length of vapor header (eq. (52)), ft

SDP/P* fractional pressure drop in tubes

DP/PLH fractional pressure drop in liquid header

Z tube length required for condensing and subcooling (eq. (106)), ft

TLV temperature of fluid at interface, ^{O}R

Z/D tube length to diameter ratio

The third line of outputs is identified as:

GEE tube mass flow rate (eq. (105)), lb/(sq ft)(sec)

P* static pressure at tube inlet, lb/sq ft

FLOW A total flow area of tubes, sq ft

U(0) vapor velocity at tube inlet, ft/sec

V(0) liquid velocity at tube inlet, ft/sec

LSC tube length required for subcooling liquid (eq. (105))

V(L) liquid velocity at interface, ft/sec

TOLV tube surface temperature at interface, ^{O}R

UVH vapor velocity at vapor header inlet, ft/sec

W/PE total specific radiator weight, lb/kw

The last set of outputs includes the following:

AP planform area of panel (eq. (111)), sq ft

AR panel aspect ratio, W'/Z

QR/WR panel specific-heat-rejection rate, Btu/(hr)(lb)

QR panel heat-rejection rate, Btu/hr

QVH/QREJ fraction of heat radiated by vapor header X'_{VH}

APRIME prime area required to reject panel heat load, $Q_r/\epsilon\sigma T_2^4$

QUAL* quality at tube inlet (eq. (54))

QVH SML vapor header heat-rejection rate (eq. (56)), Btu/lb

T* static temperature at tube inlet, ^{O}R

QREJ/W specific-heat-rejection rate for entire radiator, Btu/(hr)(lb)

The Parametric Program has two additional outputs:

WTR radiator panel weight, lb

WTOT total radiator weight, lb

MINIMUM WEIGHT PROGRAM PRINTOUT

EFFECT OF POWER LEVEL, T2, and P(0), FOR POTASSIUM - BERYLLIUM

T1 = 0.24600E 04	T2 = 0.17000E 04	DTSC = 0.10000E 03	ETAT = 0.75000E 00	QP = 0.
DP/PVH = 0.20000E-01	PE = 0.10000E 04	ETAG = 0.90000E 00	KP = 0.90000E 00	VLH = 0.40000E 01
PANELS = 0.40000E 01	(DP/P*)T = 0.50000E-01			
ALPHA = 0.53000E-10	BETA = 0.13400E 01	A LIL = 0.17500E 01	RHO P = 0.44000E-00	VBAR = 0.98400E 05
K H = 0.11500E 01	FBAR = 0.10000E 01	KF = 0.51500E 02	KT = 0.51500E 02	RHOT = 0.11500E 03
RHOF = 0.11500E 03	ET = 0.39700E 10	N = 0.	P(N) = 0.99500E 00	TAU = 0.50000E 03
RHOC = 0.53000E 03	DELCVH = 1.00000E-02			
MU L = 0.93100E-04	MU G = 0.59700E-05	RHOL = 0.42570E 02	P2 = 0.85120E 03	CP G = 0.12680E-00
CP L = 0.18420E-00	R = 0.37970E 02			
WBAR = 0.26725E 03	QUAL2 = 0.83838E 00	QIN = 0.94835E 03	ETHERM = 0.28181E-00	WDOT = 0.58390E 01
ETAC = 0.21136E-00	T2/T1 = 0.69106E 00	H = 0.86730E 03	RHOG = 0.13187E-01	

DI IN.	L IN.	T SML IN.	K	DELTA IN.	TEMP O	DELC IN.	RHOG*	N	DVH
0.37500E-00	0.18244E 01	0.78224E-01	0.60734E 01	0.49593E-00	0.16185E 04	0.17500E-01	0.96157E-02	0.46400E 03	0.10168E 01
0.62500E 00	0.19299E 01	0.92299E-01	0.40839E 01	0.48821E-00	0.16473E 04	0.25000E-01	0.10832E-01	0.21300E 03	0.88036E 00
0.87500E 00	0.20629E 01	0.10747E-00	0.32689E 01	0.48769E-00	0.16577E 04	0.35000E-01	0.11331E-01	0.12300E 03	0.80076E 00
0.11250E 01	0.21927E 01	0.12258E-00	0.28170E 01	0.48890E-00	0.16629E 04	0.45000E-01	0.11594E-01	0.80000E 02	0.74592E 00

DLH	WVH	WLH	WR/PE	Y	(SDP/P*)T	DP/PLH	Z	TLV	Z/D
0.10448E-00	0.21602E 04	0.66802E 03	0.32568E 01	0.97586E 02	0.49323E-01	0.50284E-01	0.48928E 01	0.16257E 04	0.15657E 03
0.10448E-00	0.93449E 03	0.33018E 03	0.38388E 01	0.48880E 02	0.49592E-01	0.21992E-01	0.94995E 01	0.16531E 04	0.18239E 03
0.10448E-00	0.54122E 03	0.20931E 03	0.44522E 01	0.31014E 02	0.50410E-01	0.13273E-01	0.14623E 02	0.16625E 04	0.20054E 03
0.10448E-00	0.36033E 03	0.14921E 03	0.50652E 01	0.22063E 02	0.52525E-01	0.92232E-02	0.20241E 02	0.16668E 04	0.21590E 03

GEE	P*	FLOW A	U(O)	V(O)	LSC	V(L)	TOLV	UVH	W/PE
0.16407E 02	0.59630E 03	0.35588E-00	0.12173E 04	0.14488E 02	0.14775E-00	0.38542E-00	0.16110E 04	0.22861E 03	0.60850E 01
0.12867E 02	0.68312E 03	0.45380E-00	0.93124E 03	0.10923E 02	0.26805E-00	0.30225E-00	0.16396E 04	0.30493E 03	0.51035E 01
0.11368E 02	0.71874E 03	0.51363E 00	0.81006E 03	0.94603E 01	0.40464E-00	0.26705E-00	0.16498E 04	0.36857E 03	0.52027E 01
0.10574E 02	0.73747E 03	0.55223E 00	0.74734E 03	0.87027E 01	0.55549E 00	0.24838E-00	0.16546E 04	0.42476E 03	0.55748E 01

AP	AR	QR/WR	QR	QVH/QREJ	APRIME	QUAL*	QVH'SML	T*	QREJ/W
0.95494E 03	0.99725E 01	0.41289E 04	0.13447E 08	0.14467E-00	0.10443E 04	0.71363E 00	0.10820E 03	0.16332E 04	0.25836E 04
0.92867E 03	0.25727E 01	0.38385E 04	0.14735E 08	0.62744E-01	0.11443E 04	0.78425E 00	0.46927E 02	0.16609E 04	0.30806E 04
0.90700E 03	0.10605E 01	0.34033E 04	0.15152E 08	0.36211E-01	0.11767E 04	0.80715E 00	0.27082E 02	0.16705E 04	0.30218E 04
0.89315E 03	0.54500E 00	0.30293E 04	0.15344E 08	0.23996E-01	0.11917E 04	0.81769E 00	0.17947E 02	0.16753E 04	0.28201E 04

PARAMETRIC PROGRAM PRINTOUT

POTASSIUM - BERYLLIUM   PE = 1000

T1 = 0.24600E 04	T2 = 0.17000E 04	DTSC = 0.10000E 03	ETAT = 0.75000E 00	QP = 0.
DP/PVH = 0.20000E-01	PE = 0.10000E 04	ETAG = 0.90000E 00	KP = 0.90000E 00	VLH = 0.40000E 01
PANELS = 0.40000E 01	(DP/P*)T = 0.50000E-01			
ALPHA = 0.53000E-10	BETA = 0.13400E 01	A LIL = 0.17500E 01	RHO P = 0.44000E-00	VBAR = 0.98400E 05
K H = 0.11500E 01	FBAR = 0.10000E 01	KF = 0.51500E 02	KT = 0.51500E 02	RHOT = 0.11500E 03
RHOF = 0.11500E 03	ET = 0.39700E 10	N = 0.	P(N) = 0.99500E 00	TAU = 0.50000E 03
RHOC = 0.53000E 03	DELCVH = 1.00000E-02			
MU L = 0.93100E-04	MU G = 0.59700E-05	RHOL = 0.42570E 02	P2 = 0.85120E 03	CP G = 0.12680E-00
CP L = 0.18420E-00	R = 0.37970E 02			
WBAR = 0.26725E 03	QUAL2 = 0.83838E 00	QIN = 0.94835E 03	ETHERM = 0.28181E-00	WDOT = 0.58390E 01
ETAC = 0.21136E-00	T2/T1 = 0.69106E 00	H = 0.86730E 03	RHOG = 0.13187E-01	
TABETA = 0.10000E-01	FVH = 0.85000E 00	TST = 0.50000E-03	BJBA4 = 0.40000E 01	FMES = 0.10000E 03
TST1 = 1.00000E-04			TABETA = 0.10000E 01	

FLR = 0.20000E 01   FNC = 0.10000E 01

DI IN.	L IN.	T SML IN.	K	DELTA IN.	TEMP O	DELC IN.	RHOG*	N	DVH
0.37500E-00	0.14286E 01	0.49183E-01	0.54025E 01	0.50929E 00	0.16321E 04	0.17500E-01	0.10222E-01	0.50200E 03	0.99893E 00
0.50000E-00	0.15431E 01	0.58805E-01	0.43767E 01	0.50155E 00	0.16454E 04	0.20000E-01	0.10798E-01	0.32300E 03	0.92601E 00
0.62500E 00	0.16700E 01	0.69767E-01	0.37892E 01	0.49748E-00	0.16525E 04	0.25000E-01	0.11120E-01	0.22500E 03	0.87308E 00
0.75000E 00	0.17999E 01	0.81721E-01	0.34034E 01	0.49497E-00	0.16571E 04	0.30000E-01	0.11333E-01	0.16600E 03	0.83237E 00

DLH	WVH	WLH	WR/PE	Y	(SDP/P*)T	DP/PLH	Z	TLV	Z/D
0.10448E-00	0.19773E 04	0.62783E 03	0.33878E 01	0.89643E 02	0.49582E-01	0.43078E-01	0.49395E 01	0.16401E 04	0.15806E 03
0.10448E-00	0.12676E 04	0.43062E 03	0.36527E 01	0.62303E 02	0.49100E-01	0.28115E-01	0.71765E 01	0.16525E 04	0.17224E 03
0.10448E-00	0.89934E 03	0.32237E 03	0.39528E 01	0.46968E 02	0.49368E-01	0.20508E-01	0.95613E 01	0.16587E 04	0.18358E 03
0.10448E-00	0.68144E 03	0.25525E 03	0.42483E 01	0.37349E 02	0.48615E-01	0.15951E-01	0.12037E 02	0.16628E 04	0.19260E 03

GEE	P*	FLOW A	U(O)	V(O)	LSC	V(L)	TOLV	UVH	W/PE
0.15165E 02	0.63956E 03	0.38503E-00	0.10768E 04	0.13087E 02	0.14802E-00	0.35624E-00	0.16244E 04	0.23684E 03	0.59930E 01
0.13258E 02	0.68072E 03	0.44042E-00	0.94026E 03	0.11254E 02	0.20648E-00	0.31144E-00	0.16378E 04	0.27561E 03	0.53509E 01
0.12181E 02	0.70370E 03	0.47937E-00	0.86184E 03	0.10223E 02	0.26966E-00	0.28613E-00	0.16448E 04	0.31004E 03	0.51745E 01
0.11465E 02	0.71887E 03	0.50928E 00	0.80862E 03	0.95430E 01	0.33569E-00	0.26933E-00	0.16494E 04	0.34110E 03	0.51850E 01

AP	AR	QR/WR	QR	QVH/QREJ	APRIME	QUAL*	QVH'SML	T*	QREJ/W
0.88558E 03	0.90742E 01	0.40347E 04	0.13669E 08	0.13057E-00	0.10615E 04	0.72578E 00	0.97652E 02	0.16478E 04	0.26233E 04
0.89422E 03	0.43408E 01	0.39420E 04	0.14399E 08	0.84121E-01	0.11182E 04	0.76584E 00	0.62915E 02	0.16602E 04	0.29381E 04
0.89814E 03	0.24561E 01	0.37395E 04	0.14782E 08	0.59790E-01	0.11480E 04	0.78682E 00	0.44718E 02	0.16666E 04	0.30383E 04
0.89916E 03	0.15514E 01	0.35329E 04	0.15009E 08	0.45329E-01	0.11656E 04	0.79929E 00	0.33902E 02	0.16706E 04	0.30321E 04

WTR	WTOT
0.33878E 04	0.59930E 04
0.36527E 04	0.53509E 04
0.39528E 04	0.51745E 04
0.42483E 04	0.51850E 04

APPENDIX C

EFFECT OF SPACE SINK TEMPERATURE ON RADIATOR PERFORMANCE

To simplify the development of both the Parametric and the Minimum Weight Programs, it was assumed that the effect of the equivalent space sink temperature on the heat-rejection characteristics of a space radiator can be neglected. In some cases, however, radiator design temperatures may be sufficiently low so that the effects of the environment sink temperature may be of some consequence. It is of interest therefore to appreciate how sink temperature might affect the results of the basic programs. Environment sink temperature will influence the radiator design by (1) affecting the value of ϵN_c for maximum Q_{rej}/W, (2) changing the magnitude of the finned-tube effectiveness η_r^*, and (3) reducing the net heat radiated and thereby increasing the required area and weight for a given heat-rejection load.

The inclusion of a sink temperature T_s into the development of the equation that describes the value of ϵN_c that corresponds to minimum finned-tube weight in the Minimum Weight Program indicates that the value of ϵN_c for minimum weight decreases as the value of the sink temperature ratio $\theta_s = T_s/T_o$ is increased. Figure 23 shows the calculated variation of ϵN_c with sink temperature ratio. A sink temperature ratio of 0.5 results in a reduction in the minimum weight value ϵN_c from 0.90 to 0.84. Figure 13 indicates, however, that the conductance parameter can readily be varied over a range from 1.5 to 0.5 with little effect on the value of Q_{rej}/W. Thus, the variation in ϵN_c due to sink temperature would have little overall effect on the radiator weight.

The finned-tube thermal effectiveness, which can be expressed as a function of space sink temperature, is determined in a manner similar to the development of equation (25) and is given as

$$\eta_r^* = \frac{1 - \theta_s^4 + \frac{L}{R_o}\left[\int_0^1 \left(2 - \theta^4 - \theta_s^4\right)(F_{X-1} + F_{X-2})dX - \frac{\dot{\theta}_{X=0}}{N_c}\right]}{\left(1 + \frac{L}{R_o}\right)\left(1 - \theta_s^4\right)} \tag{C1}$$

where $\theta_{X=0}$ is also a function of θ_s and obtained from the solution of the differential equation describing the fin temperature profile:

$$\frac{d^2\theta}{dX^2} = N_c\left[\theta^4 - \theta_s^4 - \left(1 - \theta_s^4\right)\left(F_{X-1} + F_{X-2}\right)\right] \tag{C2}$$

The results of calculations of equation (C1) shown in figure 24 indicate that only a small reduction in finned-tube thermal effectiveness occurs with increasing sink temperature ratio. For a sample case of $N_c = 1$ and

$L/R_o = 10$, chosen because of the sensitivity to changes in θ_s, there is a reduction in effectiveness of less than 2 percent when the space sink temperature ratio θ_s is increased from 0 to 0.6.

The effect of space sink temperature on the radiator planform area is given by the following expression:

$$A_p = \frac{Q_{rej} X_{tf}^{\prime}}{2\sigma T_o^4 (1 - \theta_s^4) \eta_{act}^*} \tag{C3}$$

It is seen that an increase in the sink temperature ratio will increase the planform area of the radiator by noting that the factor $1 - \theta_s^4$ and η_{act}^* both get smaller as the space sink temperature ratio increases. For the sample case when $\theta_s = 0.5$, $N_c = 1$, and $L/R_o = 10$, the required planform area will increase 9 percent over the area determined at $\theta_s = 0$.

For high-power-level generation systems, the effect of sink temperature is expected to be negligible, since high power levels will require high radiating temperatures to minimize radiator size and weight. For a 1-megawatt system radiating at 1700° R and a space sink temperature of 520° R, θ_s will be about 0.3. This ratio would have less than a 1-percent effect on finned-tube thermal effectiveness and radiator planform area and weight.

APPENDIX D

APPARENT EMISSIVITY OF AN ISOTHERMAL CENTRAL FINNED-TUBE CAVITY

The development of the equations describing the finned-tube thermal effectiveness given in the analysis section were based on the assumption that both the fin and the tube surfaces acted as blackbodies to incident and emitted radiation. This assumption was used to limit the number of independent variables and allow a simplified solution of the differential equation describing the fin temperature profile.

For proper treatment of the effect of surface emissivity less than unity on the thermal effectiveness of a finned-tube radiator, a complete analysis employing the net radiation method (ref. 7) involving absorptivity and reflectivity would be required. This would prove to be a difficult and lengthy calculation to cover the range of parameters of interest. In many instances the results of the blackbody analysis are simply multiplied by the surface hemispherical emissivity, which results in a pessimistic determination of the finned-tube heat rejection. To provide for the inclusion of the effect of real surfaces with emissivities < 1.0 in a simplified although approximate manner, the concept of the apparent emissivity of an isothermal cavity formed by the fin and tube was used. This procedure introduces an apparent emissivity for the configuration, which does not exceed the value that would be obtained by using the exact formulation of the problem.

The analysis required to specify this apparent emissivity makes use of the enclosure theory and the net radiation method. Additional assumptions required for the analysis are

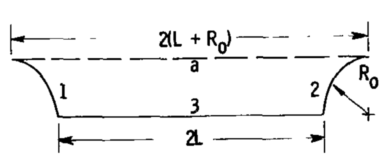
(1) The directional distribution of the energy reflected will be governed by Lambert's diffuse energy concept, which states that the reflected energy density is uniform in all directions.

(2) All emitted energy from a surface is also diffusely distributed over all angular directions.

(3) All surfaces act as gray-body emitters, that is, radiate with a spectral emissivity independent of wavelengths.

(4) The fin is assumed isothermal and at the same temperature as the tubes.

The fin and tube geometry used in the analysis is given by the accompanying sketch. The surface a is an imaginary surface that will have the same temperature as surfaces 1, 2, and 3. Energy leaving surface a does not affect the radiosities B_1, B_2, or B_3 since the surface is transparent to radiant energy. It is also assumed that $\epsilon_1 = \epsilon_2 = \epsilon_3 =$ constant. Energy incident on imaginary surface a is defined as



$$H_a = \bar{\epsilon}\sigma T^4 = B_1F_{a-1} + B_2F_{a-2} + B_3F_{a-3} \tag{D1}$$

where $\bar{\epsilon}$ is denoted as the apparent emissivity and B is defined as the radiosity of a surface and for surfaces 1, 2, and 3 is

$$B_1 = \epsilon\sigma T^4 + (1 - \epsilon)(B_2F_{1-2} + B_3F_{1-3}) \tag{D2a}$$

$$B_2 = \epsilon\sigma T^4 + (1 - \epsilon)(B_1F_{2-1} + B_3F_{2-3}) \tag{D2b}$$

$$B_3 = \epsilon\sigma T^4 + (1 - \epsilon)(2B_1F_{3-1}) \tag{D2c}$$

It is obvious that $B_1 = B_2$; thus, the radiosities are equal to

$$B_1 = B_2 = \frac{-\epsilon\sigma T^4(1 + F_{1-3} - \epsilon F_{1-3})}{F_{1-2} - \epsilon F_{1-2} - 1 + 2(1 - \epsilon)^2F_{1-3}F_{3-1}} \tag{D3a}$$

$$B_3 = \epsilon\sigma T^4 - \frac{2(1 - \epsilon)F_{3-1}\epsilon\sigma T^4(1 + F_{1-3} - \epsilon F_{1-3})}{F_{1-2} - \epsilon F_{1-2} - 1 + 2(1 - \epsilon)^2F_{1-3}F_{3-1}} \cdot \tag{D3b}$$

Substitute equations (D3a) and (D3b) into equation (D1) and solve the result for $\bar{\epsilon}$:

$$\bar{\epsilon} = \epsilon F_{a-3} + \frac{2\epsilon(1 + F_{1-3} - \epsilon F_{1-3})\left[F_{a-1} + F_{a-3}F_{3-1}(1 - \epsilon)\right]}{1 + \epsilon F_{1-2} - F_{1-2} - 2(1 - \epsilon)^2F_{1-3}F_{3-1}} \tag{D4}$$

where the view factors are defined by the following expressions obtained from geometric considerations:

$$F_{1-2} = 1 - \frac{2}{\pi}\left[1 + \frac{2}{\frac{R_o}{L}}\left(1 - \sqrt{\frac{R_o}{L} + 1}\right) + \cos^{-1}\left(\frac{\frac{R_o}{L}}{\frac{R_o}{L} + 2}\right)\right] \tag{D5}$$

$$F_{1-3} = \frac{2}{\pi}\left[\frac{1}{\frac{R_o}{L}}\left(1 - \sqrt{\frac{R_o}{L} + 1}\right) + \frac{1}{2}\cos^{-1}\left(\frac{\frac{R_o}{L}}{\frac{R_o}{L} + 2}\right)\right] \tag{D6}$$

$$F_{a-3} = \frac{1}{\sqrt{\frac{R_o}{L} + 1}} - \frac{1}{2}\left(\frac{1}{1 + \frac{L}{R_o}}\right)\cos^{-1}\left(\frac{\frac{R_o}{L}}{\frac{R_o}{L} + 2}\right) \tag{D7}$$

$$F_{a-1} = \frac{1}{2} - \frac{1}{2}\left[\frac{1}{1 + \frac{R_o}{L}} - \frac{\pi}{2}\left(\frac{1}{1 + \frac{L}{R_o}}\right)F_{1-3}\right] \tag{D8}$$

$$F_{3-1} = \frac{\pi}{4}\frac{R_o}{L}F_{1-3} \tag{D9}$$

Results of the numerical solutions of equations (D4) to (D9) are shown in figure 7 where apparent emissivity of the finned-tube cavity is plotted against aspect ratio for three values of hemispherical emissivity.

Once the apparent emissivity of the configuration has been obtained, the overall gray-body effectiveness can be calculated from the expression

$$\eta^*_{act} = \bar{\epsilon}\eta^*_r \tag{D10}$$

APPENDIX E

COMPUTER PROGRAMS

Minimum Weight Program

```
$IBFTC MAIN    NOLIST,NOREF,DECK
C
      DIMENSION HSLV(6,4),BCDUMY(12),A(5),B(5),C(5),D(5),E(5),F(5),
     1DIIN(4),FLNIN(4),TSMALI(4),CAYKPR(4),DELTAI(4),TEMPO(4),
     2DELCIN(4),RHOGSR(4),FNPRNT(4),DVHPRT(4),DLHPRT(4),WVHPRT(4),
     3WLHPRT(4),YPRINT(4),SDPOPS(4),DPPLHP(4),BIGZPT(4),GEEPRT(4),
     4PSTOR(4),FLOWA(4),UZEROP(4),VZEROP(4)    ,ELSC(4),VLIQP(4),TOLV(4),
     5UVHP(4),RADWP(4),ASTARP(4),ASPECT(4),QROWPP(4),QRPRT(4),QVHOQR(4),
     6APRIM(4),QUALS(4),SPQVH(4),TSTR(4),QREJAW(4),TLVPRT(4),ZOD(4),
     7WPOPE(4),FMPRNT(4)
C
      COMMON HSLV,A,ALIL,ALPHA,APRIME,ASTAR,B,BETA,BIGZ,C,CAPN,CAYH,
     1CAYK,CHI,CPG,CPL,D,DELC,DELCLH,DELCVH,DELTA,DI,DIAT,DLA,
     2DLH,DPOPLH,DPOPS,DPOPVH,DPSUM,DRLDX,DTSC,DVH,DXSUM,E,
     3ELSBC,EM2,ET,F,FHH,FLN,FMESH,FMUG,FMUL,FPRIME,GAMT04,KOL,NFINAL,
     4PANEL,PCHALL,PHI,PIE,PRES2,PSTAR,QALSTR,QS,QUAL2,QVH,R,RADW,
     5RHOC,RHOF,RHOG,RHOGS,RHOL,RHOP,RHOT,RLP,SIGE,TAU,THERKF,THERKT,TL,
     6TLO,TO,TSMALL,TSTA,TSTAR,TUBEA,T2,T3,UVH,UZERO,VBAR,VLH,VLIQ,
     7WDOT,WLH,WR,WVH,Y,ZN,KUO,VZERO
C
C                          MINIMUM WEIGHT PROGRAM.
C
C
C                          THE MAIN PROGRAM READS AND WRITES ALL OF THE
C                          INPUTS AND OUTPUTS, AND DOES THE CYCLE ANALYSIS.
C
C
    1 PIE=3.1415926
      SIGMA=1.713E-9
      EPSL=0.9
      SIGE=SIGMA*EPSL
      FMESH=30.
      TSTA=0.5000E-03
C
C                          THE FOLLOWING READ STATEMENTS RESPECTIVELY
C
C                          1) READ THE CONSTANTS FOR THE ENTHALPY AND
C                             ENTROPY CURVE FITS.
C                               A) HL
C                               B) SL
C                               C) HV
C                               D) SV
C
C                          2) READ THE CONSTANTS FOR THE RL AND PHI-G
C                             VERSUS CHI CURVE FITS.
C
C                          3) READ THE METEOROID PROTECTION CONSTANTS.
C
C                          4) READ THE TITLE OF THIS RUN.
C
C                          5) READ THE THERMODYNAMIC CYCLE CONDITIONS
C                             AND SEVERAL INPUTS FOR THE RADIATOR DESIGN.
C
    2 READ   (5,212)((HSLV(I,J),I=1,6),J=1,4)
      READ   (5,202)((A(I),B(I),C(I),D(I),E(I),F(I)),I=1,5)
      READ    (5,201)ALPHA,BETA,VBAR,ALIL,FPRIME,RHOP
    3 READ    (5,203)FLUID,(BCDUMY(I),I=1,12)
      READ    (5,201)T1,T3,DTSC,ETAT,QP,DPOPVH,PE,ETAG,CAYP,PCHAL2,VLH,
     1PANEL,DPOPS
      T6=T1
      T2=T3
```

```
      T4=T3-DTSC
C
C
      WRITE  (6,228)
      WRITE (6,213)
      WRITE  (6,214)
      WRITE  (6,203)FLUID,(BCDUMY(I),I=1,12)
      WRITE  (6,214)
      WRITE  (6,207)T1,T2,DTSC,ETAT,QP,DPOPVH,PE,ETAG,CAYP,VLH,PANEL,
     1DPOPS
      WRITE  (6,214)
      WRITE  (6,219)ALPHA,BETA,ALIL,RHOP,VBAR
C
      HL4=HSFIT(T4,1)
      HL3=HSFIT(T3,1)
      HL6=HSFIT(T6,1)
      HV1=HSFIT(T1,3)
      SL3=HSFIT(T3,2)
      SL6=HSFIT(T6,2)
      SV2PP=HSFIT(T2,4)
      SV1=HSFIT(T1,4)
      HV2PP=HSFIT(T2,3)
      FHH=HV2PP-HL3
      Q63=HL6-HL3
      Q34=HL3-HL4
      QIN=Q34+Q63+T1*(SV1-SL6)
      WBAR=Q63+T1*(SV1-SL6)-T3*(SV1-SL3)-QP
      QS  =QIN-WBAR*ETAT
      T2OT1=T2/T1
      WDOT=0.948*PE/(CAYP*ETAG*WBAR*ETAT)
      ETHERM=WBAR/QIN
      ETAC=ETAT*ETHERM
      QUAL2=(T3*(SV1-SL3)+WBAR*(1.-ETAT))/(T3*(SV2PP-SL3))
C
C    IF(PCHAL2) IS POSITIVE, THEN ALL OF THE ENTROPIES AND ENTHALPIES
C    FOR THE VARIOUS CYCLE POINTS  WILL BE  PRINTED OUT.
C
      IF(PCHAL2)5,5,4
    4 WRITE  (6,205)HL4,HL3,HL6,HV1,HV2PP,SL3,SL6,SV2PP,SV1
C
C
C                            READ THE ADDITIONAL INPUTS REQUIRED FOR THE
C                            DESIGN OF THE RADIATOR.
C                            IF PCHALL IS POSITIVE, A PRINT-OUT OF
C                            THE PRESSURE DROP ANALYSIS WILL OCCUR FOR THE
C                            FINAL VALUE OF UZERO FOR EACH DIAMETER.
C
C
    5 READ  (5,201)CAYH       ,THERKF,THERKT,RHOT,RHOF,ET,FN,PN,TAU,
     1RHOC,DELCVH,PCHALL
      READ   (5,201)FMUL,FMUG,RHOL,PRES2,CPG,CPL,R,DISTRT,DELDI,READ
C
C
      N=FN
      RHOG=PRES2/(R*T2)
      IF(CAYH)7,6,7
    6 CAYH=1.15
    7 WRITE  (6,210)CAYH,FPRIME,THERKF,THERKT,RHOT,RHOF,ET,FN,PN,TAU,
     1RHOC,DELCVH
      WRITE  (6,211)FMUL,FMUG,RHOL,PRES2,CPG,CPL,R
    8 WRITE  (6,204)WBAR,QUAL2,QIN,ETHERM,WDOT,ETAC,T2OT1,FHH,RHOG
```

```
C
      DI=DISTRT/12.0+3.*DELDI/12.0
      DO 17 M=1,4
      I=5-M
      IF(RHOC)14,14,9
    9 IF(DI-0.0208333)10,10,11
   10 DELC=0.00125
      GO TO 14
   11 IF(DI-0.041666)12,12,13
   12 DELC=0.00125+0.02*(DI-0.0208333)
      GO TO 14
   13 DELC=0.04*DI
   14 CALL GUIDE(M,N,PN)
      IF(KOL)15,15,124
  124 RADWP(I)=0.0
      QREJAW(I)=0.0
      QROWPP(I)=0.0
      GO TO 16
   15 DIIN(I)=12.*DI
      QREJ=QS-QP
      ASTAR=Y*BIGZ/EM2
      APRIME=(3600.0*WDOT*QS-QVH)/(SIGE*T2**4)
      FLNIN(I)=12.*FLN
      TSMALI(I)=12.*TSMALL
      CAYKPR(I)=CAYK
      DELTAI(I)=12.*DELTA
      TEMPO(I)=TO
      DELCIN(I)=12.*DELC
      RHOGSR(I)=RHOGS
      FNPRNT(I)=CAPN
      DVHPRT(I)=DVH
      DLHPRT(I)=DLH
      WVHPRT(I)=WVH
      WLHPRT(I)=WLH
      WPOPE(I)=WR/PE
      YPRINT(I)=Y
      SDPOPS(I)=DPSUM/PSTAR
      DPPLHP(I)=DPOPLH
      BIGZPT(I)=BIGZ
      TLVPRT(I)=TL
      ZOD(I)=BIGZ/DI
      GEEPRT(I)=WDOT/(CAPN*TUBEA)
      PSTOR(I)=PSTAR
      FLOWA(I)=TUBEA*CAPN
      UZEROP(I)=UZERO
      VZEROP(I)=VZERO
      ELSC(I)=ELSBC
      VLIQP(I)=VLIQ
      TOLV(I)=TLO
      UVHP(I)=UVH
      RADWP(I)=RADW/PE
      ASTARP(I)=ASTAR
      IF(PANEL-2.0)121,121,122
  122 ASPECT(I)=Y/2.0/BIGZ
      GO TO 123
  121 ASPECT(I)=Y/BIGZ
  123 QR=3600.0*WDOT*QS-QVH
      QROWPP(I)=QR/WR
      QRPRT(I)=QR
      QVHOQR(I)=QVH/(3600.0*WDOT*QREJ)
      APRIM(I)=APRIME
```

```
      QUALS(I)=QALSTR
      SPQVH(I)=QVH/(3600.0*WDOT)
      TSTR(I)=TSTAR
      QREJAW(I)=QREJ*3600.0*WDOT/RADW
   16 DI=DI-DELDI/12.0
   17 CONTINUE
      WRITE   (6,220)
      WRITE   (6,221)((DIIN(I),FLNIN(I),TSMALI(I),CAYKPR(I),DELTAI(I),
     1TEMPO(I),DELCIN(I),RHOGSR(I),FNPRNT(I), DVHPRT(I)),I=1,4)
      WRITE  (6,222)
      WRITE  (6,221)((DLHPRT(I),WVHPRT(I),WLHPRT(I),WPOPE(I),YPRINT(I),
     1SDPOPS(I),DPPLHP(I),BIGZPT(I),TLVPRT(I),ZOD(I)),I=1,4)
      WRITE  (6,224)
      WRITE  (6,221)((GEEPRT(I),PSTOR(I),FLOWA(I),UZEROP(I),VZEROP(I),
     1ELSC(I),VLIQP(I),TOLV(I),UVHP(I),RADWP(I)),I=1,4)
      WRITE  (6,226)
      WRITE  (6,221)((ASTARP(I),ASPECT(I),QROWPP(I),QRPRT(I),QVHOQR(I),
     1APRIM(I),QUALS(I),SPQVH(I),TSTR(I),QREJAW(I)),I=1,4)
      IF(READ-1.0)3,2,2
  202 FORMAT(5E12.8)
  201 FORMAT(10E8.5)
  203 FORMAT(13A6)
  204 FORMAT(1H0,8X,6HWBAR =E12.5,7X,7HQUAL2 =E12.5,9X,5HQIN =E12.5,6X,
     18HETHERM =E12.5,8X,6HWDOT =E12.5/1H ,8X,6HETAC =E12.5,7X,7HT2/T1 =
     2E12.5,11X,3HH =E12.5,8X,6HRHOG =E12.5)
  205 FORMAT(1H0,3X,5HHL4 =E12.5,3X,5HHL3 =E12.5,3X,5HHL6 =E12.5,3X,
     15HHV1 =E12.5,3X,7HHV2PP =E12.5,5X,5HSL3 =E12.5/1H ,3X,5HSL6 =E12.5
     2,1X,7HSV2PP =E12.5,3X,5HSV1 =E12.5)
  207 FORMAT (1H0,10X,4HT1 =E12.5,10X,4HT2 =E12.5,8X,6HDTSC =E12.5,8X,
     16HETAT =E12.5,10X,4HQP =E12.5/1H ,6X,8HDP/PVH =E12.5,10X,4HPE =
     2E12.5,8X,6HETAC =E12.5,10X,4HKP =E12.5,9X,5HVLH =E12.5/1H ,6X,
     38HPANELS =E12.5,4X,10H(DP/P*)T =E12.5)
  210 FORMAT(1H0,8X,6H K H =E12.5,8X,6HFBAR =E12.5,10X,4HKF =E12.5,
     110X,4HKT =E12.5,8X,6HRHOT =E12.5/1H ,8X,6HRHOF =E12.5,10X,4HET =
     2E12.5,11X,3HN =E12.5,8X,6HP(N) =E12.5,9X,5HTAU =E12.5/1H ,8X,
     36HRHOC =E12.5,6X,8HDELCVH =E12.5)
  211 FORMAT (1H0,8X,6HMU L =E12.5,8X,6HMU G =E12.5,8X,6HRHOL =E12.5,
     110X,4HP2 =E12.5,8X,6HCP G =E12.5/1H ,8X,6HCP L =E12.5,11X,3HR =
     2E12.5)
  212 FORMAT (6E12.8)
  213 FORMAT(1H1)
  214 FORMAT(1H )
  219 FORMAT(1H0,7X,7HALPHA =E12.5,8X,6HBETA =E12.5,7X,7HA LIL =E12.5,
     17X,7HRHO P =E12.5,8X,6HVBAR =E12.5)
  221 FORMAT(1H ,10E13.5)
  220 FORMAT(1H0,4X,6HDI IN.,8X,5HL IN.,6X,9HT SML IN.,8X,1HK,8X,9HDELTA
     1 IN.,5X,6HTEMP O,6X,8HDELC IN.,7X,5HRHOG*,10X,1HN,11X,3HDVH)
  222 FORMAT(1H0,6X,3HDLH,10X,3HWVH,10X,3HWLH,9X,5HWR/PE,10X,1HY,7X,
     19H(SDP/P*)T,6X,6HDP/PLH,10X,1HZ,11X,3HTLV,10X,3HZ/D)
  224 FORMAT(1H0,6X,3HGEE,10X,2HP*,9X,6HFLOW A,8X,4HU(O),9X,4HV(O),10X,
     13HLSC,9X,4HV(L),9X,4HTOLV,10X,3HUVH,8X,6H  W/PE)
  226 FORMAT(1H0,6X,2HAP,11X,2HAR,10X,5HQR/WR,9X,2HQR,8X,8HQVH/QREJ,6X,
     16HAPRIME,8X,5HQUAL*,6X,7HQVH-SML,9X,2HT*,8X,6HQREJ/W)
  228 FORMAT(1HL/1HL)
      END
$IBFTC GUIDE    NOLIST,NOREF,DECK,DEBUG
C
      SUBROUTINE GUIDF(M,N,PN)
C
      DIMENSION HSLV(6,4),A(5),B(5),C(5),D(5),E(5),F(5)
      COMMON HSLV,A,ALIL,ALPHA,APRIME,ASTAR,B,BETA,BIGZ,C,CAPN,CAYH,
```

```
     1CAYK,CHI,CPG,CPL,D,DELC,DELCLH,DELCVH,DELTA,DI,DIAT,DLA,
     2DLH,DPOPLH,DPOPS,DPOPVH,DPSUM,DRLDX,DTSC,DVH,DXSUM,E,
     3ELSBC,EM2,ET,F,FHH,FLN,FMESH,FMUG,FMUL,FPRIME,GAMTO4,KOL,NFINAL,
     4PANEL,PCHALL,PHI,PIE,PRES2,PSTAR,QALSTR,QS,QUAL2,QVH,R,RADW,
     5RHOC,RHOF,RHOG,RHOGS,RHOL,RHOP,RHOT,RLP,SIGE,TAU,THERKF,THERKT,TL,
     6TLO,TO,TSMALL,TSTA,TSTAR,TUBEA,T2,T3,UVH,UZERO,VBAR,VLH,VLIQ,
     7WDOT,WLH,WR,WVH,Y,ZN,KUO,VZERO
C
C     THIS SUBROUTINE CONTROLS THE ITERATIONS ON QVH AND UZERO.
C
      IF(M-1)1,1,2
    1 TO=T2
      UZERO=400.0
      DELTA=0.02
      QVH=50.0*WDOT*3600.0
      FLN=0.10
      SVEL=SQRT(32.14*ET/RHOT)
      DELTA1=2.*FPRIME*ALIL
      DELTA2=(RHOP*62.45/RHOT)**0.5
      DELTA3=(VBAR/SVEL)**0.66667
      DELTA4=(6.747E-5/RHOP)**0.3333
      CALL ENBARS(N,PN,ENBAR)
      DELTA5=(ALPHA*TAU/(ENBAR*(BETA+1.)))**(1./(3.*BETA))
      DLA=DELTA1*DELTA2*DELTA3*DELTA4*DELTA5
    2 UL=0.0
      UH=0.0
      MP=0
      CAPNS=0
      NFINAL=0.
    3 KUO=0
      L=0
    4 KQVH=0
    5 KCAPN=0
    6 CALL SUBW
    7 QALSTR=QUAL2-QVH/(FHH*WDOT*3600.0)
      IF(QALSTR)25,25,4
   40 RHOGS=PSTAR/(R*TSTAR)
    8 CAPN=4.*WDOT*QALSTR/(PIE*RHOGS*UZERO*DI*DI)
    9 QVHSV=QVH
      CALL SUBH(L)
      QVHTST=0.5*TSTA*(QVHSV+QVH)
      IF(ABS(QVHSV-QVH)-QVHTST)12,12,11
   11 KQVH=KQVH+1
      IF(KQVH-25)5,5,25
      QVHSV=QVH
   12 IF(NFINAL)10,10,71
   10 CALL SUBK(MP)
      DELUO=100.0
      IF(MP)42,42,43
   43 DELUO=DELUO/2.0
      UZERO=UZERO-DELUO*2.0
      MP=0
      GO TO 22
   42 DPOPS1=DPSUM/PSTAR
      DPTST=0.5*TSTA*(DPSUM+DPOPS*PSTAR)
      IF(DPOPS)64,65,64
   65 DPTST=.001
   64 IF(ABS(DPOPS*PSTAR-DPSUM)-DPTST)35,35,21
   35 IF(ABS(CAPNS-CAPN)-0.5)26,26,21
   21 UZEROS=UZERO
   13 IF(DPOPS*PSTAR-DPSUM)14,14,17
```

```
   14 UZEROH=UZERO
      DPSUMH=DPSUM
      IF(UL)16,16,15
   15 UH=1.0
      GO TO 20
   16 UZERO=UZERO-DELUO
      UH=1.0
      GO TO 22
   17 UZEROL=UZERO
      DPSUML=DPSUM
      IF(UH)19,19,18
   18 UL=1.0
      GO TO 20
   19 UZERO=UZERO+DELUO
      UL=1.0
      GO TO 22
   20 DELU =UZEROH-UZEROL
      DDELP=DPSUMH-DPSUML
      DDELP1=DPSUMH-DPOPS*PSTAR
      UZERO=UZEROH-DELU *DDELP1/DDELP
   22 KUO=KUO+1
      IF(UZERO-2500.0)41,41,25
   41 IF(KUO-30)61,61,26
   61 CAPNS=CAPN
      GO TO 4
   25 KOL=1
      GO TO 34
   26 KOL=0
C
C                           THIS SECTION ROUNDS OFF THE NUMBER OF TUBES TO
C                           AN INTEGER NUMBER.
C
   30 UZERON=UZERO
      CAPNNS=CAPN
      JCAPN=CAPN
      FCAPN=JCAPN
      IF(ABS(CAPN-FCAPN)-0.5)27,27,28
   28 CAPN=FCAPN+1.0
      GO TO 63
   27 CAPN=FCAPN
   63 FCAPNS=CAPN
   29 UZERO=UZEROS-(CAPNS-FCAPNS)*(UZEROS-UZERON)/(CAPNS-CAPNNS)
      IF(UZERO-2500.0)31,31,32
   32 UZERO=2500.0
   31 NFINAL=1
      IF(UZERO-100.0)59,59,37
   59 UZERO=100.0
   37 KUO=KUO+1
      UZEROS=UZERON
      CAPNS=CAPNNS
      IF(KUO-50)60,60,25
   60 UZERON=UZERO
      GO TO 6
   71 CAPNNS=CAPN
C
      DEBUG FCAPNS,UZEROS,CAPNS,UZERON,CAPNNS,UZERO,CAPN
C
      IF(ABS(CAPN-FCAPNS)-0.001)33,33,29
   33 L=1
      CAPN=FCAPNS
      CALL SUBK(MP)
```

```
      CALL SUBH(L)
   34 RETURN
      END
$IBFTC SUBW     NOLIST,NOREF,DECK
C
      SUBROUTINE SUBW
      DIMENSION HSLV(6,4),A(5),B(5),C(5),D(5),E(5),F(5)
C
      COMMON HSLV,A,ALIL,ALPHA,APRIME,ASTAR,B,BETA,BIGZ,C,CAPN,CAYH,
     1CAYK,CHI,CPG,CPL,D,DELC,DELCLH,DELCVH,DELTA,DI,DIAT,DLA,
     2DLH,DPOPLH,DPOPS,DPOPVH,DPSUM,DRLDX,DTSC,DVH,DXSUM,E,
     3ELSBC,EM2,ET,F,FHH,FLN,FMESH,FMUG,FMUL,FPRIME,GAMT04,KOL,NFINAL,
     4PANEL,PCHALL,PHI,PIF,PRES2,PSTAR,QALSTR,QS,QUAL2,QVH,R,RADW,
     5RHOC,RHOF,RHOG,RHOGS,RHOL,RHOP,RHOT,RLP,SIGE,TAU,THERKF,THERKT,TL,
     6TLO,TO,TSMALL,TSTA,TSTAR,TUBEA,T2,T3,UVH,UZERO,VBAR,VLH,VLIQ,
     7WDOT,WLH,WR,WVH,Y,ZN,KUO,VZERO
C
C
C                            THIS SUBROUTINE SOLVES FOR T*,P*,TO,DELTA, AND
C                            THE FIN GEOMETRY.
C
      XPTF=1.-QVH/(QS   *WDOT*3600.0)
      CO2GJH=1.0/(2.*32.2*778.*FHH)
      TSTAR=T2*(1.-CAYH*UZERO*UZERO*CO2GJH)
      PSTARA=2.*32.2*R*TSTAR
      PSTAR=PSTARA*PRES2/(PSTARA+CAYH*UZERO*UZERO)
      KTDL=0
    1 DIAT=DI+2.*(DELC+DELTA)
      GAMT04=SIGE*DIAT*0.5*ALOG(DIAT/(DI+2.*DELC))
      KTO=0
    2 TO3=TO**3
      CT041=GAMT04*TO3*TO
      CT042=-THERKT*(TO-TSTAR)
      TOSAV=TO
      TO=TO-(CT041-CT042)/(4.*TO3*GAMT04+THERKT)
      TOTST=0.5*TSTA*(TOSAV+TO)
      IF(ABS(TOSAV-TO)-TOTST)4,4,3
    3 KTO=KTO+1
      IF(KTO-25)2,2,4
    4 KTL=0
      FT=0.85
      FF=0.85
      ETAF=0.55
      FVH=0.85
      GAML3=8.*RHOF*SIGE*TO3/THERKT
      GAML2=9.43*RHOF*SIGE*FT*TO3*DIAT/(THERKT*FF*ETAF)
      GAM=0.9*PIE*(RHOC*DELC*(DI+DELC)+RHOT*DELTA*(DIAT-DELTA))
    5 CL3=GAML3*FLN**3
      CL2=GAM-GAML2*FLN**2
      FLNSV=FLN
      FLN=FLN-(CL3-CL2)/(FLN*(3.*GAML3*FLN+2.*GAML2))
      FLNTST=0.5*TSTA*(FLNSV+FLN)
      IF(ABS(FLNSV-FLN)-FLNTST)7,7,6
    6 KTL=KTL+1
      IF(KTL-25)5,5,7
    7 AVC1=PIE*DIAT*XPTF*QS   *3600.*WDOT
      AVC2=PIE*DIAT*FT+4.*ETAF*FF*FLN
      AVC3=SIGE*TO3*TO
      AVCC3=SIGE*T2**4
      AV=AVC1/(AVC2*AVC3)+QVH/(FVH*AVCC3)
      DAV=(1./AVC3)*(2.*AVC1/(AVC2*DIAT)-AVC1*2.*PIE*FT/(AVC2*AVC2))
```

```
      DELTAS=DELTA
      C103B=1./(3.*BETA)
      DELTA=DELTA-(DELTAS-DLA*AV**C103B)/(1.+DLA*C103B*DAV*AV**(C103B-1.
     1))
      DLTST=0.5*TSTA*(DELTAS+DELTA)
      IF(ABS(DELTAS-DELTA)-DLTST)9,9,8
    8 KTDL=KTDL+1
      IF(KTDL-25)1,1,9
    9 DIAT=DI+2.*(DELC+DELTA)
      QT=PIE*FT*DIAT*SIGE*T03*T0
      QF=2.*ETAF*FLN*SIGE*T03*T0*FF
      CAYK=(QT+2.*QF)/(SIGE*PIE*DI*T03*T0)
      ZN=(3600.0*WDOT*QS   -QVH)/(QT+2.*QF)
      TSMALL=2.*SIGE*FLN*FLN*T0**3/(0.9*THERKF)
   10 RETURN
      END
$IBFTC SUBK     NOLIST,NOREF,DECK
C
      SUBROUTINE SUBK(MP)
C
      DIMENSION HSLV(6,4),A(5),B(5),C(5),D(5),E(5),F(5)
C
      COMMON HSLV,A,ALIL,ALPHA,APRIME,ASTAR,B,BETA,BIGZ,C,CAPN,CAYH,
     1CAYK,CHI,CPG,CPL,D,DELC,DELCLH,DELCVH,DELTA,DI,DIAT,DLA,
     2DLH,DPOPLH,DPOPS,DPOPVH,DPSUM,DRLDX,DTSC,DVH,DXSUM,E,
     3ELSBC,EM2,ET,F,FHH,FLN,FMESH,FMUG,FMUL,FPRIME,GAMT04,KOL,NFINAL,
     4PANEL,PCHALL,PHI,PIE,PRES2,PSTAR,QALSTR,QS,QUAL2,QVH,R,RADW,
     5RHOC,RHOF,RHOG,RHOGS,RHOL,RHOP,RHOT,RLP,SIGE,TAU,THERKF,THERKT,TL,
     6TLO,TO,TSMALL,TSTA,TSTAR,TUBEA,T2,T3,UVH,UZERO,VBAR,VLH,VLIQ,
     7WDOT,WLH,WR,WVH,Y,ZN,KUO,VZERO
C
C
C                           THIS SUBROUTINE DOES THE PRESSURE DROP ANALYSIS
C                           FOR TWO-PHASE TURBULENT-TURBULENT FLOW.
C                           THE ANALYSIS TAKES FMESH NUMBER OF SMALL
C                           SECTIONS OF THE TUBE, WHERE DELTA-WL IS THE
C                           SAME FOR EACH SECTION.
C                           DELTA-X AND DELTA-P ARE THEN FOUND FOR EACH
C                           SECTION, AND THE DELTA-P,S ARE ADDED TO FIND
C                           THE TOTAL DELTA-P FOR THE TUBE.
C
      IF(NFINAL)3,3,1
    1 IF(PCHALL)3,3,2
    2 PRINT=1.0
    3 QS1=CAYK*SIGE*PIE*DI/3600.
      TOX1=SIGE*DIAT*ALOG(DIAT/(DI+2.*DELC))/(2.0*THERKT)
      W=WDOT/CAPN
      FJH=778.*FHH
      GJ=778.*32.2
      TUBEA=PIE*DI*DI/4.0
      GDI3=32.2*DI*DI*DI
      WL=(1.-QALSTR)*W
      WG=W-WL
      DELWL=WG/FMESH
      P=PSTAR
      T=TSTAR
      TX=T
      PX=P
      TOX=TO
      DISTX=0.0
      DPSUM=0.0
```

```
      DXSUM=0.0
      RHOGS=PSTAR/(TSTAR*R)
      CHIC1=(RHOGS/RHOL)*(FMUL/FMUG)**0.2
      CHI=SQRT((WL/WG)**1.8*CHIC1)
      CALL RLAFEG(CHI,PHI,RLP,DRLDX,A,B,C,D,E,F)
      VZERO=WL/(RHOL*TUBEA*RLP)
      WL1=WL+DELWL/2.0
      WG1=W-WL1
      IF(PRINT)5,5,4
    4 DIPRNT=12.*DI
      WRITE  (6,102)DIPRNT
      WRITE  (6,100)
    5 MESH=FMESH
      DO 8 J=1,MESH
    6 RHOGA=P/(R*T)
      CHIC1=(RHOGA/RHOL)*(FMUL/FMUG)**0.2
      CHI=SQRT(((WL1/WG1)**1.8)*CHIC1)
      CALL RLAFEG(CHI,PHI,RLP,DRLDX,A,B,C,D,E,F)
      RGP=1.-RLP
      V=WL1/(RLP*TUBEA*RHOL)
      U=WG1/(RGP*TUBEA*RHOGA)
      V2=V*V
      U2=U*U
      U2COEF=1.-0.9*CHI*W*DRLDX/(RGP*WL1)
      V2COEF=1.-0.9*CHI*W*DRLDX/(RLP*WG1)
      REGP=4.*WG1/(PIE*DI*FMUG)
      DPXF=-PHI*PHI*0.092*FMUG*FMUG*REGP**1.8/(GDI3*RHOGA)
      DPMDW1=0.9*DRLDX*CHI*W
      DPMDW2=2.0-DPMDW1/(RGP*WL1)
      DPMDW3=2.-DPMDW1/(RLP*WG1)
      DPMDW4=RHOGA*U2*RGP*DPMDW2/(32.2*WG1)
      DPMDW5=RHOL*V2*RLP*DPMDW3/(32.2*WL1)
      DPMDWX=DPMDW4-DPMDW5
      DPC1=(CPL*WL1+CPG*WG1)*T/(FJH*RHOGA)
      TOX=TX/(1.+TOX1*TOX**3)
      QS2=QS1*TOX**4
      DX1=QS2+DPC1*DPXF
      DX2=FHH-V2*V2COEF/GJ+U2*U2COEF/GJ-DPC1*DPMDWX+(U2-V2)/(2.*GJ)
      DX=DX2*DELWL/DX1
      DP=-DPMDWX*DELWL-DPXF*DX
      DELT=-T*DP/(FJH*RHOGA)
      IF(PRINT)7,7,9
    9 WLT=WL1*CAPN
      DISTX=DISTX+DX/2.
      WRITE  (6,101)DISTX,WLT,P,T,RHOGA,U,V,CHI,RLP,PHI,DPXF
      DISTX=DISTX+DX/2.
    7 P=P-DP
      IF(P)10,10,11
   10 MP=1
      GO TO 12
   11 T=T+DELT
      TX=T
      PX=P
      WL1=WL1+DELWL
      WG1=W-WL1
      DPSUM=DPSUM+DP
      DXSUM=DXSUM+DX
    8 CONTINUE
      TL=TX
      TLO=TOX
      VLIQ=W/(TUBEA*RHOL)
```

```
      CONSTG=4.*W/(PIE*DI*DI)
      ELSBC1=300.*CPL*CONSTG/(CAYK*SIGE)*DI
      ELSBC2=1./(TL-DTSC)**3-1./TL**3
      ELSBC=ELSBC1*ELSBC2
      BIGZ=DXSUM+ELSBC
C
      PRINT=0.0
C
      MP=0
   12 RETURN
  100 FORMAT(1H ,3X,8HPOSITION,6X,2HWL,11X,1HP,11X,1HT,9X,5HRHO G,9X,
     11HU,11X,1HV,11X,1HX,11X,2HRL,6X,5HPHI G,4X,6HDPF/DX)
  101 FORMAT(1H ,9E12.4,F8.5,E12.4)
  102 FORMAT(1HL,71HPRINT-OUT OF STEP-BY-STEP PRESSURE DROP CALCULATIONS
     1 FOR TUBE DIAMETER=F5.3,3HIN.)
      END
$IBFTC SUBH    NOLIST,NOREF,DECK
C
      SUBROUTINE SUBH(L)
      DIMENSION HSLV(6,4),A(5),B(5),C(5),D(5),E(5),F(5)
C
      COMMON HSLV,A,ALIL,ALPHA,APRIME,ASTAR,B,BETA,BIGZ,C,CAPN,CAYH,
     1CAYK,CHI,CPG,CPL,D,DELC,DELCLH,DELCVH,DELTA,DI,DIAT,DLA,
     2DLH,DPOPLH,DPOPS,DPOPVH,DPSUM,DPLDX,DTSC,DVH,DXSUM,E,
     3ELSBC,EM2,ET,F,FHH,FLN,FMESH,FMUG,FMUL,FPRIME,GAMT04,KOL,NFINAL,
     4PANEL,PCHALL,PHI,PIE,PPES2,PSTAR,QALSTR,QS,QUAL2,QVH,R,RADW,
     5RHOC,RHOF,RHOG,RHOGS,RHOL,RHOP,RHOT,RLP,SIGE,TAU,THERKF,THERKT,TL,
     6TLO,TO,TSMALL,TSTA,TSTAR,TUBEA,T2,T3,UVH,UZERO,VBAR,VLH,VLIQ,
     7WDOT,WLH,WR,WVH,Y,ZN,KUO,VZERO
C
C                         THIS SUBROUTINE SETS THE VALUES OF M1, M2, M3,
C                         DEPENDING UPON THE NUMBER OF PANELS. IT THEN
C                         FINDS THE HEADER SIZES,QVH, AND THE RADIATOR
C                         COMPONENT WEIGHTS.
C
      IF(L)1,1,6
    1 IF(PANEL-2.0)2,3,4
    2 EM1=1.0
      EM2=1.0
      EM3=1.0
      GO TO 5
C
    3 EM1=2.0
      EM2=0.5
      EM3=1.0
      GO TO 5
C
    4 EM1=1.0
      EM2=0.5
      EM3=0.5
C
    5 Y=2.0*EM2*CAPN*(FLN+0.5*DI+DELC+DELTA)
      DVHC1=0.00357*Y*FMUG**0.2
      DVHC2=(2.*WDOT*QUAL2*EM1)**1.8*EM1
      DVHC3=RHOG*PRES2*DPOPVH*PIE**1.8
      DVH=(DVHC1*DVHC2/DVHC3)**(1./4.8)
      FVH=0.85
      QVH=2.0944*SIGE*FVH*Y*DVH*T2**4
      GO TO 9
    6 DLH=(2.0*EM3*WDOT/(PIE*RHOL*VLH))**0.5
      RELH2=(RHOL*DLH*VLH/FMUL)**0.2
```

```
      DPLH=0.00051*RHOL*VLH*VLH*EM1*Y/(RELH2*DLH)
      DPOPLH=DPLH/(PSTAR-DPSUM)
      DELCLH=0.04*DLH
      IF(DELCLH-0.01)8,8,7
    7 DELCLH=0.01
    8 WVH1=(DVH+DELCVH)*(Y    +DELCVH)*DELCVH*RHOC
      WVH2=(DVH+2.*DELCVH+DELTA)*(Y    +2.*DELCVH+DELTA)*RHOT*DELTA
      WVH=0.666667*3.1415926*(WVH1+WVH2)
      WLH1=RHOL*DLH*DLH/4.0+RHOC*DELCLH*(DLH+DELCLH)
      WLH2=RHOT*DELTA*(DLH+DELTA+2.*DFLCLH)
      WLH=Y*(WLH1+WLH2)*PIE/EM2
      WP1=RHOC*DELC*(DI+DELC)
      WP2=RHOT*DELTA*(DI+2.*DELC+DELTA)
      WP3=4.0*1.713E-09*RHOF*(FLN*TO)**3/THERKF
      WR=CAPN*BIGZ*(WP3+PIE*(WP1+WP2))
      RADW=WVH+WLH+WR
      UVH=EM1*2.*WDOT*QUAL2/(DVH*DVH*RHOG*PIE)
    9 RETURN
      END
$IBFTC HSFIT    NOLIST,NOREF,DECK
      FUNCTION HSFIT(T,J)
C
C
      DIMENSION HSLV(6,4)
C
      COMMON HSLV
C
C     THIS  SUBROUTINE OR PROGRAM FUNCTION IS THE ENTHALPY AND ENTROPY
C    CURVE FIT.
C
C
       X           =HSLV(1,J)+T*(HSLV(2,J)+T*(HSLV(3,J)+T*(HSLV(4,J)
     1+T*(HSLV(5,J)+T*(HSLV(6,J))))))
      HSFIT=X
C
      RETURN
      END
$IBFTC RLAFEG   NOLIST,NOREF,DECK,DEBUG
C
      SUBROUTINE RLAFEG(CHI,PHI,RLP,DRLDX,A,B,C,D,E,F)
C
      DIMENSION HSLV(6,4),A(5),B(5),C(5),D(5),E(5),F(5)
C
C    THIS  SUBROUTINE  IS  THE  CURVE  FIT  SUBROUTINE  FOR  THE  RL
C     AND  PHI-G  CURVE FITS.
C
      IF(CHI-100.)1,1,2
    1 ELX=ALOG10(CHI)
      IF(.001-CHI)3,3,5
    5 NA=0
      GO TO 6
    3 NA=4.+ELX
      GO TO 6
    2 CHI=100.0
      GO TO 1
    6 IF(NA)7,7,8
    7 PHI=1.0
      DFEGDX=0.
      GO TO 11
    8 PHI=ELX*(ELX*A(NA)+B(NA))+C(NA)
      PHI=10.0**PHI
```

```
C
C     RL  VERSUS  CHI  CURVE  FIT  FROM  THIS  POINT  ON.
C
   11 IF(NA)12,12,13
   12 RLP=10.**ELX
      DRLDX=10.**ELX/CHI
      GO TO 14
   13 RLP=ELX*(ELX*D(NA)+E(NA))+F(NA)
      RLP=10.**RLP
      DRLDX=RLP*(2.*ELX*D(NA)+E(NA))/CHI
   14 RETURN
      END
$IBFTC ENBARS  NOLIST,NOREF,DECK
      SUBROUTINE ENBARS (N,POFN,ENBAR)
      DIMENSION PATCH (20)
C     DIMENSION PATCH (20)
      IF (N) 1,1,2
    1 ENBAR= -ALOG(POFN)
      GO TO 3
    2 IF (N-2) 4,5,5
    4 DELP = 1.0- POFN
      ENBAR= SQRT( -2.0* ALOG(POFN))
   13 EMINN = EXP(-ENBAR)
      IF (DELP - .005) 6,6,7
    7 EFOP = (1.0+ ENBAR) * EMINN - POFN
      GO TO 8
    6 ALFK = .5 * ENBAR ** 2
      FOP = ALFK
      CJM2 = 1.
      CJM1 = 2.
      DO 9 J = 3,16
      IF (ABS(ALFK/FOP) - 1.E-10) 8,8,1
   10 CJ = J
      ALFK = -ALFK * CJM1 * ENBAR / CJ / CJM2
      FOP = FOP + ALFK
      CJM2 = CJM1
    9 CJM1 = CJ
      EFOP = FOP - DELP
    8 EFPRIM = - ENBAR * EMINN
      FOFP = EFOP/EFPRIM
      IF (ABS(FOFP/ENBAR) - 5.E -5) 3,3,11
   11 ENBAR = ENBAR - FOFP
      GO TO 13
    5 WRITE (6,12)
    3 RETURN
   12 FORMAT (17HK N IS TOO LARGE )
      END
```

```
$DATA
   -.10916+2     .22663+0  -3.18786-5    7.6005-9                                 HL     POT
   .201365+0    .580306-3   -.31184-6    .90984-10  -.10291-13                    SL     POT
   .961893+3     .21716+0   -.69939-4    .117904-7                                HV     POT
    4.5497+0   -7.1959-3    6.6733-6   -3.2936-9    8.2908-13   -8.353-17SV      POT
3.4400606-022.3920305-014.4800374-01    -.84205-1     .51266+0
   -.70418+07.2800108-023.7840032-015.7280021-01    -.84205-1
    .51266+0   -.70418+01.3680009-014.9280009-016.2320000-01
   -.84205-1     .51266+0   -.70418+01.2999988-014.8100011-01
6.3199998-01    -.84205-1     .51266+0   -.70418+07.9999027-02
5.6200306-016.0099775-01    -.84205-1     .51266+0    -.70418+0
53000-1013400+0198400+0517500+0110000+0144000+00
 EXAMPLE RUN FOR THE KREBS, HALLER, AND AUER REPORT-POTASSIUM-BERYLLIUM
24600+0417000+0410000+0375000+           020000-011        490000+0090000+00
40000+0140000+0105000+0
11500+0151500+0251500+0211500+0311500+0339700+100        099500+0050000+0353000+03
10000-01
93100-0459700-0542570+0285120+0312680+0018420+0037970+0237500+0025000+0010000+01
```

```
$IBFTC ETAA     NOLIST,NOREF,DECK,DEBUG
      SUBROUTINE ETAA(ETA,FLR,FLAM,THSO,FMESH,TST)
C
C                    TO OBTAIN ETA USING SUBS. INTGRL AND DEQ2
C
      DEBUG ETA,FLR,FLAM,THSO,FMESH,TST
      DIMENSION FX(501),TH(501),FAX(501)
      POW=4.0
      MESH=FMESH
      CALL INTGRL(MESH,FAX,FLR)
      MOSH=MESH+1
      DO 20 J=1,MOSH
      TH(J)=1.0
   20 CONTINUE
      C=FLAM
      THSO4=THSO**4
      THSO41=1.-THSO4
      MOSH=MESH+1
      DO 4 J=1,MOSH
      FX(J)=FLAM*(-THSO4-THSO41*FAX(J))
    4 CONTINUE
      MASH=MESH+1
      DEBUG (FX(J),J=1,MASH)
      CALL DEQ2(TH,FX,C,POW,MESH,TST)
      SLOPE=-(1.-TH(2))*FMESH
      MASH=MESH
      THSO4=THSO**4
      THA=1.-(1.-TH(2))/4.0
      THA4=THA**4
      FRL=1./FLR
      FRL2=FRL*FRL
      X=1./(4.*FMESH)
      FAX1=1.-0.5*SQRT((FRL+X)**2-FRL2)/(FRL+X)-0.5*SQRT((FRL+2.-X)**2-
     1FRL2)/(FRL+2.-X)
      FINTG=2.-THA4-THSO4
      FINTGA=0.5*FINTG*FAX1
      DO 3 J=2,MASH
      THA4=TH(J)**4
```

```
      FINTG=2.-THA4-THS04
      FINTGA=FINTGA+FINTG*FAX(J)
    3 CONTINUE
      MCSH=MESH+1
      THA4=TH(MCSH)**4
      FINTG=2.-THA4-THS04
      FINTGL=(FINTGA+0.5*FINTG*FAX(MCSH))/FMESH
      THS041=1.-THS04
      ETA=(THS041+FLR*FINTGL-FLR*SLOPE/FLAM)/(THS041*(1.+FLR))
      RETURN
      END
$IBFTC DEQ2     NOLIST,NOREF,DECK,DEBUG
      SUBROUTINE DEQ2(TH,FX,C,POW,MESH,TST)
C     B. LINDOW  VERSION  OF  KALABA,S METHOD
      DIMENSION TH(501),B(500),D(500),E(500),F(500),FX(501)
      FMESH=MESH
      DX=1./FMESH
      DX2=DX*DX
      DGC=C*POW*DX2
      PM1=POW-1.0
      FDC=(-PM1)*C*DX2
      KCNT=0
      DEBUG FMESH,DX,DX2,DGC,PM1,FDC
   14 THPOW=TH(2)**POW
      B(1)=2.+DGC*THPOW/TH(2)
      D(1)=FDC*THPOW+DX2*FX(2)-1.0
      E(1)=B(1)
      F(1)=1.0
C
      THPOW=TH(3)**POW
      B(2)=2.+DGC*THPOW/TH(3)
      D2=FDC*THPOW+DX2*FX(3)
      E(2)=1.-E(1)*B(2)
      F(2)=E(1)
      D(2)=D(1)+D2*E(1)
C
      MASH=MESH-1
      DO 27 J=3,MASH
      THPOW=TH(J+1)**POW
      B(J)=2.+DGC*THPOW/TH(J+1)
      D2=FDC*THPOW+DX2*FX(J+1)
      E(J)=F(J-1)+B(J)*E(J-1)
      F(J)=-E(J-1)
      D(J)=D(J-1)-D2*F(J-1)
   27 CONTINUE
C
      THPOW=TH(MESH+1)**POW
      B(MESH)=2.+DGC*THPOW/TH(MESH+1)
      D2=FDC*THPOW+DX2*FX(MESH+1)
      E(MESH)=2.*F(MESH-1)+B(MESH)*E(MESH-1)
      D(MESH)=+2.*D(MESH-1)-D2*F(MESH-1)
      TH(MESH+1)=D(MESH)/E(MESH)
C
      MOSH=MESH+1
      DEBUG KCNT
      DEBUG(FX(J),J=1,MOSH)
      DEBUG(TH(J),J=1,MOSH)
      DEBUG (B(J),J=1,MESH)
      DEBUG (F(J),J=1,MESH)
      DEBUG (F(J),J=1,MESH)
      DEBUG (D(J),J=1,MESH)
```

```
C
   30 KTST=0
      MOSH=MESH-1
      DO 35 J=1,MOSH
      JJ=MESH-J+1
      THSV=TH(JJ)
      JO=JJ-1
      IF(J-MESH+1)31,2,2
   31 TH(JJ)=(-TH(JJ+1)*F(JO)+D(JO))/E(JO)
      GO TO 3
    2 TH(JJ)=(TH(JJ+1)*F(JO)-D(JO))/E(JO)
    3 J=J
C
      DEBUG THSV,JJ,TH(JJ)
C
      IF(ABS(THSV-TH(JJ))-TST)35,35,32
   32 KTST=KTST+1
   35 CONTINUE
C
      DEBUG KCNT,KTST
C
   36 IF(KTST)45,45,37
   37 KCNT=KCNT+1
      IF(KCNT-25)14,14,40
   40 WRITE (6,41)KCNT,KTST
   41 FORMAT(1H ,22HTROUBLE SEE SUBR. DEQ2,4X,5HKCNT=I3,4X,5HKTST=I3)
   45 RETURN
      END
$IBFTC INTGRL  NOLIST,NOREF,DECK,DEBUG
      SUBROUTINE INTGRL(MESH,FAX,FLR)
      DIMENSION FAX(501)
      FMESH=MESH
      DELX=1./FMESH
      FRL=1./FLR
      MOSH=MESH+1
      DEBUG FMESH,MESH,DELX,THSO,THSO4,THSO41,FLR,FRL
      X=0.0
      DO 1 J=1,MOSH
      FXA1=FRL+X
      FXA2=FXA1*FXA1
      FXA=SQRT(FXA2-FRL*FRL)/FXA1
      FXB1=FRL+2.0-X
      FXB2=FXB1*FXB1
      FXB=SQRT(FXB2-FRL*FRL)/FXB1
      FAX(J)=1.-0.5*(FXA+FXB)
      X=X+DELX
    1 CONTINUE
      MASH=MESH+1
      DEBUG (FAX(J),J=1,MASH)
      RETURN
      END
$IBFTC EEAA    LIST,REF,DECK
      SUBROUTINE EEAA(FLR,EAA)
      DIMENSION EAR(5)
      EAR(1)=0.917
      EAR(2)=0.908
      EAR(3)=0.905
      EAR(4)=0.902
      EAR(5)=0.9
      IF(FLR-2.0)11,14,14
   11 FLR1=0.0
```

```
      DFLR=2.0
      J=1
      GO TO 30
   14 IF(FLR-4.0)16,19,19
   16 FLR1=2.0
      DFLR=2.0
      J=2
      GO TO 30
   19 IF(FLR-8.0)22,25,25
   22 FLR1=4.0
      DFLR=4.0
      J=3
      GO TO 30
   25 IF(FLR-16.0)27,40,40
   27 FLR1=8.0
      DFLR=8.0
      J=4
   30 DEAA= (FLR-FLR1)/DFLR*(EAR(J)-EAR(J+1))
      EAA=EAR(J)-DEAA
      GO TO 45
   40 EAA=0.9
   45 RETURN
      END
```

```
      SUBROUTINE TABLE (ETATOT,FLR,FNC,TABL)
C
C
      DIMENSION TABL(13,36)
C
C
C
    6 FLSAVE=FLR
   13 IF(FNC)79,18,18
   18 IF(FLR-10.0)20,100,100
   20 IF(FLR-8.0)310,301,301
  310 IF(FLR-6.0)21,101,101
   21 IF(FLR-4.0)22,102,102
   22 IF(FLR-3.0)311,302,302
  311 IF(FLR-2.0)23,103,103
   23 IF(FLR-1.5)312,303,303
  312 IF(FLR-1.0)71,104,104
  104 I=1
      DELL=0.5
      FLRT=1.0
      GO TO 60
  103 I=3
      DELL=1.0
      FLRT=2.0
      GO TO 60
  102 I=5
      DELL=2.0
```

```
      FLRT=4.0
      GO TO 60
  101 I=6
      DELL=2.0
      FLRT=6.0
      GO TO 60
  303 I=2
      FLRT=1.5
      DELL=0.5
      GO TO 60
  302 I=4
      FLRT=3.0
      DELL=1.0
      GO TO 60
  301 I=7
      FLRT=8.0
      DELL=2.0
      GO TO 60
  100 IF(FLR-15.)299,299,300
  300 IF(FLR-20.0)99,99,30
   30 IF(FLR-30.0)98,98,31
   31 IF(FLR-50.0)97,97,32
  299 I=8
      FLRT=10.0
      DELL=5.0
      GO TO 60
   99 I=9
      DELL=5.0
      FLRT=15.0
      GO TO 60
   98 I=10
      DELL=10.0
      FLRT=20.0
      GO TO 60
   97 I=11
      DELL=20.0
      FLRT=30.0
      GO TO 60
   32 I=12
      IF(FLR-1050.0)40,41,41
   41 FLR=1050
      GO TO 40
   40 DELL=1000.0
      FLRT=50.0
      GO TO 60
   60 IF(FNC-5.0)67,70,200
  200 IF(FNC-20.0)209,211,206
  206 IF(FLR-50.0)370,370,371
  371 ETA=.145
      GO TO 372
  370 ETA=.86567785+FLR*(-.1701984+FLR*(.012712537-FLR*.000191947))
  372 WRITE   (6,110)FNC
  110 FORMAT(1H0,42HFNC OUT OF RANGE-SEE SUBROUTINE TABLE-FNC=E12.5)
      GO TO 71
  209 FJ=21.+(FNC-5.0)
      J=FJ
      FAJ=J
      FRAC=FJ-FAJ
      K=2
      GO TO 61
   67 FJ=FNC/0.25+1.0
```

```
      J=FJ
      FAJ=J
      FRAC=FJ-FAJ
      K=0
   61 DEL1=TABL(I,J)-TABL(I+1,J)
      DEL2=TABL(I,J+1)-TABL(I+1,J+1)
      FRAC1=(FLR-FLRT)/DELL
      ETA1=TABL(I,J)-DEL1*FRAC1
      ETA2=TABL(I,J+1)-DEL2*FRAC1
      ETA=ETA1-ETA2
      IF(K-1)62,72,210
  210 IF(K-2)213,213,214
   62 ETATOT=ETA1-FRAC*ETA
      SLPME=-4.0*ETA
      FLR=FLSAVE
      GO TO 71
   70 J=20
      K=1
      GO TO 61
   72 ETATOT=ETA2
      SLPME=-4.0*ETA
      FLR=FLSAVE
      GO TO 71
  213 ETATOT=ETA1-FRAC*ETA
      SLPME=-ETA
      FLR=FLSAVE
      GO TO 71
  214 ETATOT=ETA2
      SLPME=-ETA
      FLR=FLSAVE
      GO TO 71
  211 J=35
      K=3
      GO TO 61
   79 ETA=1.0
   71 RETURN
      END
```

```
$DATA
 1.000  .921  .880  .854  .834  .820  .809  .800  .792  .785  .779  .77
  .770  .766  .762  .759  .756  .754  .751  .749  .747  .740  .734  .73
  .726  .723  .720  .718  .716  .714  .713  .711  .710  .709  .708  .70
 1.000  .893  .838  .803  .777  .758  .742  .730  .719  .710  .702  .69
  .690  .684  .679  .675  .675  .667  .663  .660  .657  .648  .640  .63
  .629  .625  .621  .618  .615  .613  .610  .608  .607  .605  .603  .60
 1.000  .874  .809  .767  .736  .713  .695  .680  .667  .656  .647  .63
  .632  .626  .619  .615  .610  .605  .601  .598  .594  .583  .573  .56
  .560  .555  .550  .546  .543  .540  .537  .535  .533  .531  .529  .52
 1.000  .849  .771  .720  .684  .656  .634  .616  .601  .588  .577  .56
  .558  .550  .543  .537  .531  .526  .521  .516  .512  .498  .487  .47
  .470  .464  .458  .454  .449  .446  .443  .439  .437  .434  .432  .43
```

```
1.000   .833   .747   .692   .652   .621   .597   .577   .560   .546   .534   .52
 .513   .504   .497   .490   .483   .477   .472   .467   .462   .446   .434   .42
 .415   .408   .402   .397   .392   .388   .384   .380   .378   .375   .372   .37
1.000   .816   .721   .659   .615   .581   .555   .533   .514   .498   .484   .47
 .462   .452   .443   .435   .428   .422   .416   .410   .405   .387   .373   .36
 .352   .344   .338   .332   .326   .321   .317   .313   .310   .307   .304   .30
1.000   .806   .707   .642   .595   .560   .531   .508   .489   .472   .457   .44
 .433   .423   .414   .406   .398   .391   .384   .379   .373   .354   .340   .32
 .318   .309   .302   .295   .290   .285   .280   .276   .272   .267   .266   .26
1.000   .800   .697   .631   .583   .546   .517   .493   .473   .455   .440   .42
 .415   .405   .395   .387   .379   .372   .365   .359   .353   .334   .319   .30
 .296   .287   .279   .273   .267   .261   .257   .252   .248   .245   .242   .23
1.000   .792   .685   .615   .565   .527   .497   .472   .450   .432   .417   .40
 .391   .380   .370   .361   .353   .345   .338   .332   .326   .305   .289   .27
 .265   .256   .248   .241   .235   .229   .224   .220   .216   .212   .208   .20
1.000   .788   .678   .607   .556   .517   .486   .461   .439   .421   .405   .39
 .378   .367   .357   .348   .339   .332   .324   .318   .312   .291   .274   .26
 .250   .240   .232   .225   .218   .213   .207   .203   .199   .195   .191   .18
1.000   .783   .672   .600   .547   .508   .476   .450   .428   .409   .393   .37
 .365   .354   .344   .334   .326   .318   .311   .304   .297   .276   .259   .24
 .234   .224   .216   .208   .202   .196   .191   .186   .812   .177   .174   .17
1.000   .780   .667   .593   .540   .500   .468   .441   .417   .399   .383   .36
 .355   .344   .333   .324   .315   .307   .299   .292   .286   .264   .247   .23
 .221   .211   .203   .195   .189   .183   .177   .172   .168   .164   .160   .15
1.000   .768   .648   .580   .526   .487   .457   .432   .410   .390   .373   .35
 .342   .330   .318   .308   .300   .291   .283   .277   .272   .251   .233   .21
 .207   .196   .187   .180   .173   .167   .161   .156   .152   .147   .143   .14
  -.10916+2     .22663+0   -3.18786-5    7.6005-9                                HL    PO
   .201365+0   .580306-3   -.31184-6    .90984-10   -.10291-13                     SL    PO
   .961893+3    .21716+0   -.69939-4    .117904-7                                  HV    PO
    4.5497+0   -7.1959-3    6.6733-6   -3.2936-9    8.2908-13     -8.353-1 SV    PO
3.4400606-027.2800108-021.3680009-011.2999988-017.9999027-02
2.3920305-013.7840032-014.9280009-014.8100011-015.6200306-01
4.4800374-015.7280021-016.2320000-016.3199998-016.0099775-01
     +.192-1      +.642-1      +.1930+0     +.1070+0      +.771-1
    +.1152+0     +.2952+0     +.5528+0     +.5528+0     +.6126+0
    +.2328+0     +.4128+0     +.5416+0     +.5416+0     +.5117+0
    .30316-2     .64527-1     .24029+0
    .21347-1     .26581+0     .56351+0
    .51758-1     .29471+0     .41664+0     .20000+2     .20000+2
   -.84205-1    -.84205-1    -.84205-1    -.84205-1    -.84205-1
    .51266+0     .51266+0     .51266+0     .51266+0     .51266+0
   -.70418+0    -.70418+0    -.70418+0    -.70418+0    -.70418+0
    1037.5+0.906818182-1-.22727273-5.118333333+0.443181813-4-.18939394-
-.69444443-4 .18307288-7   -.3156-11
1POTASSIUM - COLUMBIUM   PE = 500
53   -10 134  +1 984  +5 175  +1 1    +1 44   +
 246  +4 17   +4 1    +3 75              2    -1 5    +3 9    +  9    +
 4    +1 4    +1-5    -1
 115  +1 24   +2 24   +2 53   +3 53   +3202  +10          995  +  5    +  53   +
 1    -1 0    +
 931  -4 597  -5 4257 -2 8512 +3 1268 +  1842 +  3797 +2 375  +  25    +
 0    +  85   +  5    -3 2    +1 1    +3 1    -3 1    +1
   1 18   +1
   1 75   +
```

```
$IBFTC MAIN     DECK,DEBUG
C
       DIMENSION HSLV(6,4),BCDUMY(12),A(5),B(5),C(5),D(5),E(5),F(5),
      1DIIN(4),FLNIN(4),TSMALI(4),CAYKPR(4),DELTAI(4),TEMPO(4),
      2DELCIN(4),RHOGSR(4),FNPRNT(4),DVHPRT(4),DLHPRT(4),WVHPRT(4),
      3WLHPRT(4),YPRINT(4),SDPOPS(4),DPPLUP(4),BIGZPT(4),GEFPRT(4),
      4PSTUR(4),FLOWA(4),UZEROP(4),VZEROP(4)     ,ELSC(4),VLIQP(4),TOLV(4),
      5UVHP(4),RADWP(4),ASTARP(4),ASPECT(4),GROWPP(4),QRPRT(4),QVHOQR(4),
      6APRIM(4),QUALS(4),SPQVH(4),TSTR(4),QREJAW(4),TLVPRT(4),ZOD(4),
      7WPOPE(4),FMPRNT(4),DBA(4,50),TABL(13,36),
      8FLRD(50),FNCD(50)
C
       COMMON HSLV,A,ALIL,ALPHA,APRIME,ASTAR,B,BETA,BIGZ,C,CAPN,CAYH,
      1CAYK,CHI,CPG,CPL,D,DELC,DELCLH,DELCVH,DELTA,DI,DIAT,DLA,
      2DLH,DPOPLH,DPOPS,DPOPVH,DPSUM,DRLDX,DTSC,DVH,DXSUM,E,
      3ELSBC,EM2,ET,F,FHH,FLN,FMESH,FMUG,FMUL,FPRIME,GAMTO4,KOL,NFINAL,
      4PANEL,PCHALL,PHI,PIE,PRES2,PSTAR,QALSTR,QS,QUAL2,QVH,R,RADW,
      5RHOC,RHOF,RHOG,RHOGS,RHOL,RHOP,RHOT,RLP,SIGE,TAU,THERKF,THERKT,TL,
      6TLO,TO,TSMALL,TSTA,TSTAR,TUBEA,T2,T3,UVH,UZERO,VBAR,VLH,VLIQ,
      7WDOT,WLH,WR,WVH,Y,ZN,KUO,VZERO,
      8  EPSL,ETAAS,FLR,FNC,FVH,       SIGMA,THTAS,TST,WBAR
C
C
C                             PARAMETRIC STUDY PROGRAM
C                             THE MAIN PROGRAM READS AND WRITES ALL OF THE
C                             INPUTS AND OUTPUTS, AND DOES THE CYCLE ANALYSIS
C
C
    1 PIE=3.1415926
      SIGMA=1.713E-9
      EPSL=0.9
      SIGE=SIGMA*EPSL
      FMESH=30.
      TSTA=0.5000E-03
C
C                             THE FOLLOWING READ STATEMENTS RESPECTIVELY
C
C                             1) READ THE CONSTANTS FOR THE ENTHALPY AND
C                                ENTROPY CURVE FITS.
C                                  A) HL
C                                  B) SL
C                                  C) HV
C                                  D) SV
C
C                             2) READ THE CONSTANTS FOR THE RL AND PHI-G
C                                VERSUS CHI CURVE FITS.
C
C                             3) READ THE METEOROID PROTECTION CONSTANTS.
C
C                             4) READ THE TITLE OF THIS RUN.
C
```

```
C                             5) READ THE THERMODYNAMIC CYCLE CONDITIONS
C                                AND SEVERAL INPUTS FOR THE RADIATOR DESIGN.
C
      IF(JERROR) 30,30,3
   30 READ   (5,232)((TABL(I,J),J=1,36),I=1,13)                             0640
    2 READ   (5,212)((HSLV(I,J),I=1,6),J=1,4)
      READ   (5,202)((A(I),B(I),C(I),D(I),E(I),F(I)),I=1,5)
      READ    (5,201)ALPHA,BETA,VBAR,ALIL,EPPIME,RHOP
    3 READ    (5,203)FLUID,(BCDUMY(I),I=1,12)
      READ    (5,201)T1,T3,DTSC,ETAT,QP,DPOPVH,PE,ETAG,CAYP,PCHAL2,VLH,
     1PANEL,DPOPS
      JERROR= 1
      T6=T1
      T2=T3
      T4=T3-DTSC
C
C
      WRITE   (6,228)
      WRITE (6,213)
      WRITE   (6,214)
      WRITE   (6,203)FLUID,(BCDUMY(I),I=1,12)
      WRITE   (6,214)
      WRITE   (6,207)T1,T2,DTSC,ETAT,QP,DPOPVH,PE,ETAG,CAYP,VLH,PANEL,
     1DPOPS
      WRITE   (6,214)
      WRITE   (6,219)ALPHA,BETA,ALIL,RHOP,VBAR
C
      HL4=HSFIT(T4,1)
      HL3=HSFIT(T3,1)
      HL6=HSFIT(T6,1)
      HV1=HSFIT(T1,3)
      SL3=HSFIT(T3,2)
      SL6=HSFIT(T6,2)
      SV2PP=HSFIT(T2,4)
      SV1=HSFIT(T1,4)
      HV2PP=HSFIT(T2,3)
      FHH=HV2PP-HL3
      Q63=HL6-HL3
      Q34=HL3-HL4
      QIN=Q34+Q63+T1*(SV1-SL6)
      WBAR=Q63+T1*(SV1-SL6)-T3*(SV1-SL3)-QP
      QS   =QIN-WBAR*ETAT
      T2OT1=T2/T1
      WDOT=0.948*PE/(CAYP*ETAG*WBAR*ETAT)
      ETHERM=WBAR/QIN
      ETAC=ETAT*ETHERM
      QUAL2=(T3*(SV1-SL3)+WBAR*(1.-ETAT))/(T3*(SV2PP-SL3))
C
C    IF(PCHAL2) IS POSITIVE, THEN ALL OF THE ENTROPIES AND ENTHALPIES
C    FOR THE VARIOUS CYCLE POINTS  WILL BE  PRINTED OUT.
C
      IF(PCHAL2)5,5,4
    4 WRITE   (6,205)HL4,HL3,HL6,HV1,HV2PP,SL3,SL6,SV2PP,SV1
C
C
C                            READ THE ADDITIONAL INPUTS REQUIRED FOR THE
C                            DESIGN OF THE RADIATOR.
C                            IF PCHALL IS POSITIVE, A PRINT-OUT OF
C                            THE PRESSURE DROP ANALYSIS WILL OCCUR FOR THE
C                            FINAL VALUE OF UZERO FOR EACH DIAMETER.
C
```

```
C
    5 READ   (5,201)CAYH        ,THERKF,THERKT,RHOT,RHOF,ET,FN,PN,TAU,
     1RHOC,DELCVH,PCHALL
      READ    (5,201)FMUL,FMUG,RHOL,PRES2,CPG,CPL,R,DISTRT,DELDI,READ
C
C
      N=FN
      RHOG=PRES2/(R*T2)
      IF(CAYH)7,6,7
    6 CAYH=1.15
    7 WRITE   (6,210)CAYH,FPRIME,THERKF,THERKT,RHOT,RHOF,ET,FN,PN,TAU,
     1RHOC,DELCVH
      WRITE   (6,211)FMUL,FMUG,RHOL,PRES2,CPG,CPL,R
    8 WRITE   (6,204)WBAR,QUAL2,QIN,ETHERM,WDOT,ETAC,T2OT1,FHH,RHOG
C
      READ(5,201) THTAS,FVH,TST,BJBA4,FMES ,TST1,TABETA
      READ(5,234) JRD, (FLRD(J),J=1,JRD)
      READ(5,234) JND,(FNCD(J),J=1,JND)
      BJND=JND
      BJRD= JRD
      WRITE (6,236) THTAS,FVH,TST,BJBA4,FMES ,TST1,BJRD,BJND,TABETA
      WRITE(6,238)
      JBA4= BJBA4
      DI=DISTRT/12.0+(BJBA4-1.0)*DELDI/12.0
C
C
      DO 50   JJN=1,JND
      FNC= FNCD(JJN)
C
      DO 40   JJR=1,JRD
      FLR= FLRD(JJR)
      IF (TABETA) 42,42,41
   42 CALL ETAA(ETATOT,FLR,FNC,THTAS,FMES ,TST1)
      GO TO 43
   41 CALL TABLE (ETATOT,FLR,FNC,TABL)
   43 CALL FFAA(FLR,FAA)
      ETAAS=FAA*ETATOT
C
C
      DO 17 M=1,JBA4
      I= JBA4+1-M
      IF(RHOC)14,14,9
    9 IF(DI-0.0208333)10,10,11
   10 DELC=0.00125
      GO TO 14
   11 IF(DI-0.041666)12,12,13
   12 DELC=0.00125+0.02*(DI-0.0208333)
      GO TO 14
   13 DELC=0.04*DI
   14 CALL GUIDF(M,N,PN)
      IF(KOL)15,15,124
  124 RADWP(I)=0.0
      QROWPP(I)=0.0
      GO TO 16
   15 DIIN(I)=12.*DI
      QREJ=QS-QP
      ASTAR=Y*BIGZ/EM2
      APRIME=(3600.0*WDOT*QS-QVH)/(SIGE*T2**4)
      FLNIN(I)=12.*FLN
      TSMALI(I)=12.*TSMALL
      CAYKPR(I)=CAYK
```

```
      DELTAI(I)=12.*DELTA
      TEMPO(I)=TO
      DELCIN(I)=12.*DELC
      RHOGSR(I)=RHOGS
      FNPRNT(I)=CAPN
      DVHPRT(I)=DVH
      DLHPRT(I)=DLH
      WVHPRT(I)=WVH
      WLHPRT(I)=WLH
      BIGZPT(I)=BIGZ
      WR= WBAP*CAPN*BIGZ
      DBA(I,4)= WR
      RADW= DBA(I,4) +WVH+ WLH
      DBA(I,5)= RADW
      WROPE(I)=WR/PE
      YPRINT(I)=Y
      SDPOPS(I)=DPSUM/PSTAR
      DPPLHP(I)=DPOPLH
      TLVPRT(I)=TL
      ZOD(I)=BIGZ/DI
      GEEPRT(I)=WDOT/(CAPN*TUBEA)
      PSTOR(I)=PSTAR
      FLOWA(I)=TUBEA*CAPN
      UZEROP(I)=UZERO
      VZEROP(I)=VZERO
      ELSC(I)=ELSBC
      VLIQP(I)=VLIQ
      TOLV(I)=TLO
      UVHP(I)=UVH
      RADWP(I)=RADW/PE
      ASTARP(I)=ASTAR
      IF(PANEL-2.0)121,121,122
  122 ASPECT(I)=Y/2.0/BIGZ
      GO TO 123
  121 ASPECT(I)=Y/BIGZ
  123 QR=3600.0*WDOT*QS-QVH
      QROWPP(I)=QR/WR
      QRPRT(I)=QR
      QVHOQR(I)=QVH/(3600.0*WDOT*QREJ)
      APRIM(I)=APRIME
      QUALS(I)=QALSTR
      SPQVH(I)=QVH/(3600.0*WDOT)
      TSTP(I)=TSTAR
      QREJAW(I)=QREJ*3600.0*WDOT/RADW
   16 DI=DI-DELDI/12.0
   17 CONTINUE
      WRITE (6,244) FLR,FNC
      WRITE   (6,220)
      WRITE   (6,221)((DIIN(I),FLNIN(I),TSMALI(I),CAYKPR(I),DELTAI(I),
     1TEMPO(I),DELCIN(I),RHOGSR(I),FNPRNT(I), DVHPRT(I)),I=1,JBA4)
      WRITE  (6,222)
      WRITE  (6,221)((DLHPRT(I),WVHPRT(I),WLHPRT(I),WROPE(I),YPRINT(I),
     1SDPOPS(I),DPPLHP(I),BIGZPT(I),TLVPRT(I),ZOD(I)),I=1,JBA4)
      WRITE  (6,224)
      WRITE  (6,221)((GEEPRT(I),PSTOR(I),FLOWA(I),UZEROP(I),VZEROP(I),
     1ELSC(I),VLIQP(I),TOLV(I),UVHP(I),RADWP(I)),I=1,JBA4)
      WRITE  (6,226)
      WRITE  (6,221)((ASTARP(I),ASPECT(I),QROWPP(I),QRPRT(I),QVHOQR(I),
     1APRIM(I),QUALS(I),SPQVH(I),TSTP(I),QREJAW(I)),I=1,JBA4)
      WRITE(6,242)
      WRITE (6,246)((DBA(I,J),J=4,5),I=1,JBA4)
```

```
   40 CONTINUE
   50 CONTINUE
C
C
      IF(READ-1.0)3,3,2
  202 FORMAT(5E12.8)
  201 FORMAT(10F8.5)
  203 FORMAT(13A6)
  204 FORMAT(1H0,8X,6HWBAR =F12.5,7X,7HQUAL2 =E12.5,9X,5HQIN =E12.5,6X,
     18HETHERM =F12.5,8X,6HWDOT =F12.5/1H ,8X,6HFTAC =F12.5,7X,7HT2/T1 =
     2E12.5,11X,3HH =F12.5,8X,6HRHOG =E12.5)
  205 FORMAT(1H0,3X,5HHL4 =E12.5,3X,5HHL3 =E12.5,3X,5HHL6 =E12.5,3X,
     15HHV1 =E12.5,3X,7HHV2PP =E12.5,5X,5HSL3 =E12.5/1H ,3X,5HSL6 =E12.5
     2,1X,7HSV2PP =F12.5,3X,5HSV1 =F12.5)
  207 FORMAT (1H0,10X,4HT1 =F12.5,10X,4HT2 =F12.5,8X,6HDTSC =F12.5,8X,
     16HFTAT =E12.5,10X,4HQP =F12.5/1H ,6X,8HDP/PVH =F12.5,10X,4HPE =
     2F12.5,8X,6HFTAG =E12.5,10X,4HKP =F12.5,9X,5HVLH =F12.5/1H ,6X,
     38HPANELS =E12.5,4X,10H(DP/P*)T =F12.5)
  210 FORMAT(1H0,8X,6H K H =F12.5,8X,6HFBAR =F12.5,10X,4HKF =E12.5,
     110X,4HKT =E12.5,8X,6HRHOT =E12.5/1H ,8X,6HRHOF =E12.5,10X,4HET =
     2E12.5,11X,3HN =F12.5,8X,6HP(N) =E12.5,9X,5HTAU =F12.5/1H ,8X,
     36HRHOC =F12.5,6X,8HDELCVH =F12.5)
  211 FORMAT (1H0,8X,6HMU L =E12.5,8X,6HMU G =F12.5,8X,6HRHOL =F12.5,
     110X,4HP2 =F12.5,8X,6HCP G =F12.5/1H ,8X,6HCP L =F12.5,11X,3HR =
     2F12.5)
  212 FORMAT (6F12.8)
  213 FORMAT(1H1)
  214 FORMAT(1H )
  219 FORMAT(1H0,7X,7HALPHA =E12.5,8X,6HBETA =E12.5,7X,7HA LIL =F12.5,
     17X,7HRHO P =F12.5,8X,6HVBAR =F12.5)
  221 FORMAT(1H ,10F13.5)
  220 FORMAT(1H0,4X,6HDI IN.,8X,5HL IN.,6X,9HT SML IN.,8X,1HK,8X,9HDELTA
     1 IN.,5X,6HTEMP 0,6X,8HDELC IN.,7X,5HRHOG*,10X,1HN,11X,3HDVH)
  222 FORMAT(1H0,6X,3HDLH,10X,3HWVH,10X,3HWLH,9X,5HWR/PE,10X,1HY,7X,
     19H(SDP/P*)T,6X,6HDP/PLH,10X,1H7,11X,3HTLV,10X,3H7/D).
  224 FORMAT(1H0,6X,3HGEE,10X,2HP*,9X,6HFLOW A,8X,4HU(0),9X,4HV(0),10X,
     13HLSC,9X,4HV(L),9X,4HTOLV,10X,3HUVH,8X,6H  W/PE)
  226 FORMAT(1H0,6X,2HAP,11X,2HAR,10X,5HQR/WR,9X,2HQP,8X,8HQVH/QREJ,6X,
     16HAPRIME,8X,5HQUAL*,6X,7HQVH-SML,9X,2HT*,8X,6HQREJ/W)
  228 FORMAT(1HL/1HL)
  232 FORMAT (12F6.3)
  234 FORMAT(I4,9F8.5/10F8.5)
  236 FORMAT(1H0,7X,7HTHTAS =E12.5,9X,5HFVH =E12.5,9X,5HTST =E12.5,
     1       7X,7HBJBA4 =E12.5,8X,6HFMES =E12.5/1H ,8X,6HTST1 =E12.5,
     2       9X,5HJRD =E12.5,9X,5HJND =E12.5,6X,8HTABFTA =E12.5)
  238 FORMAT(1H )
  240 FORMAT(10E13.5)
  242 FORMAT(1H0,6X,3HWTR,10X,4HWTOT)
  244 FORMAT(1H0,2X,5HFLR =F12.5,4X,5HFNC =F12.5)
  246 FORMAT(1H ,2E13.5)
      END
```

```
$IBFTC SBWLH1  LIST,REF,DECK,DEBUG
C
      SUBROUTINE SUBW
C
C                             SUBW H1   -  LINDOWS VERSION
C
      DIMENSION HSLV(6,4),A(5),B(5),C(5),D(5),E(5),F(5)
C
      COMMON HSLV,A,ALIL,ALPHA,APRIME,ASTAR,B,BETA,BIGZ,C,CAPN,CAYH,
     1CAYK,CHI,CPG,CPL,D,DELC,DELCLH,DELCVH,DELTA,DI,DIAT,DLA,
     2DLH,DPOPLH,DPOPS,DPOPVH,DPSUM,DRLDX,DTSC,DVH,DXSUM,E,
     3ELSBC,EM2,ET,F,FHH,FLN,FMESH,FMUG,FMUL,FPRIME,GAMT04,KSL,NFINAL,
     4PANEL,PCHALL,PHI,PIE,PRES2,PSTAR,QALSTR,QS,QUAL2,QVH,R,PADW,
     5RHOC,RHOF,RHOG,RHOGS,RHOL,RHOP,RHOT,RLP,SIGE,TAU,THERKF,THERKT,TL,
     6TLO,TO,TSMALL,TSTA,TSTAR,TUBEA,T2,T3,UVH,UZERO,VBAR,VLH,VLIQ,
     7WDOT,WLH,WR,WVH,Y,ZN,KUO,VZERO,
     8  EPSL,ETAAS,FLR,FNC,FVH,      SIGMA,THTAS,TST,WBAP
C
C
C                             THIS SUBROUTINE SOLVES FOR T*,P*,TO,DELTA, AND
C                             THE FIN GEOMETRY.
C
      CO2GJH=1.0/(2.*32.2*778.*FHH)
      TSTAR=T2*(1.-CAYH*UZERO*UZERO*CO2GJH)
      PSTARA=2.*32.2*R*TSTAR
      PSTAR=PSTARA*PRES2/(PSTARA+CAYH*UZERO*UZERO)
      DELBA = DELC
C
C                             CONSTANT CALC.
      THTAS2  =  THTAS*THTAS
      THTAS4  =  THTAS2*THTAS2
      THTAS5  =  1.0-THTAS4
      BETA3  =  1.0/(3.0*BETA)
      FT1  =  DI+2.0*DELBA
      FT2  =  0.5*SIGMA*EPSL  *(THTAS5)
      XVH= QVH/(QS*3600.*WDOT)
      XTF  =  1.0-XVH
      ATOT1= QS*3600.*WDOT/(SIGMA*THTAS5)
   18 ATOT2  =       PIE*XTF/(2.0*ETAAS*(1.0+FLR))
      ATOT3  =  XVH/(FVH*EPSL)
      ATOT4  =  ATOT1*(ATOT2+ATOT3)
C
C                             BEGIN T,DELTA CALC.
      KCT=0
      T= TSTAR
      TSTAR2= TSTAR*TSTAR
   22 DELTA=(ATOT4/(TSTAR2*TSTAR2))**BETA3*DLA
   43 FT6  =  FT1+2.0*DELTA
      FT7= ALOG(FT6/FT1)
      FT8  =  FT2*FT6*FT7
   45 TCU  =  T*T*T
      T44  =  TCU*T
```

```
      FT= T44*FT8 + THERKT*(T-TSTAR)
      FTD = 4.0*TCU*FT8 + THERKT
      TSV = T
      T = T-FT/FTD
   52 DTST= 0.5*(T+TSV)*TST
      IF (ABS(T-TSV)-ABS(DTST)) 60,60,5
   50 KCT = KCT+1
      IF (KCT-50) 45,45,47
   47 WRITE (6,48)KCT
C
C                        END T CALC.
   60 TCU=T*T*T
      T44=T*TCU
      ATOT = ATOT4/T44
      DELTAS = DELTA
      DELTA = ATOT**BETA3*DLA
      DEBUG DELTA,T,FT,XVH
   62 DTST = 0.5*(DELTA+DELTAS)*TST
      IF (ABS(DELTA-DELTAS)-ABS(DTST))70,70,63
   63 KCT = KCT+1
      IF (KCT-50) 43,43,66
   66 WRITE (6,48)KCT
C
C                        END DELTA CALC.
   70 ROBA=0.5*DI+DELC       +DELTA
      DIAT= 2.0*ROBA
      FLN= FLR*ROBA
      FKBA1=4.0*ROBA*ETAAS*(1.0+FLR)
      CAYK=FKBA1/(EPSL *DI*PIE)
      WBA1=T*ROBA*FLR
      WBA2=WBA1*WBA1*WBA1
   71 WBA3=4.0*RHOE *SIGMA*WBA2
      WBA4=WBA3/(THERKE*FNC)
      WBA5= RHOC*DELC*(DI+DELC)
      WBA6=RHOT*DELTA*(DI+DELC      +DELC       +DELTA)
      WBAP= PIE*(WBA5+WBA6)+WBA4
      TSMALL= 2.0*SIGMA*TCU*FLN*FLN/(THERKF*FNC)
      TO= T
      GAMTO4=SIGE*DIAT*0.5*ALOG(DIAT/(DI+2.*DELC))
      ETAF=0.55
      TO3= TO**3
      FTT= 0.85
      FF=0.85
      QT= PIE*FTT*DIAT*SIGE*TO3*TO
      QF=2.*ETAF*FLN*SIGE*TO3*TO*FF
      ZN=(3600.0*WDOT*QS   -QVH)/(QT+2.*QF)
   48 FORMAT(1H ,13HTROUBLE 50,63,I6)
   80 RETURN
      END
```

```
$IBFTC SUBK     NOLIST,NOREF,DECK,DEBUG
C
      SUBROUTINE SUBK(MP)
C
      DIMENSION HSLV(6,4),A(5),B(5),C(5),D(5),E(5),F(5)
C
      COMMON HSLV,A,ALIL,ALPHA,APRIME,ASTAR,B,BETA,BIGZ,C,CAPN,CAYH,
     1CAYK,CHI,CPG,CPL,D,DELC,DELCLH,DELCVH,DELTA,DI,DIAT,DLA,
     2DLH,DPOPLH,DPOPS,DPOPVH,DPSUM,DRLDX,DTSC,DVH,DXSUM,E,
     3ELSBC,FM2,ET,F,FHH,FLN,FMESH,FMUG,FMUL,FPRIME,GAMT04,KOL,NFINAL,
     4PANEL,PCHALL,PHI,PIE,PRES2,PSTAR,QALSTR,QS,QUAL2,QVH,R,RADW,
     5RHOC,RHOF,RHOG,RHOGS,RHOL,RHOP,RHOT,RLP,SIGE,TAU,THERKF,THERKT,TL,
     6TLO,TO,TSMALL,TSTA,TSTAR,TUBEA,T2,T3,UVH,UZERO,VBAR,VLH,VLIQ,
     7WDOT,WLH,WR,WVH,Y,ZN,KUO,VZERO,
     8  EPSL,ETAAS,FLR,FNC,FVH,PCON,THTAS,TST,WBAP
C
C
C                         THIS SUBROUTINE DOES THE PRESSURE DROP ANALYSIS
C                         FOR TWO-PHASE TURBULENT-TURBULENT FLOW.
C                         THE ANALYSIS TAKES FMESH NUMBER OF SMALL
C                         SECTIONS OF THE TUBE, WHERE DELTA-WL IS THE
C                         SAME FOR EACH SECTION.
C                         DELTA-X AND DELTA-P ARE THEN FOUND FOR EACH
C                         SECTION, AND THE DELTA-P,S ARE ADDED TO FIND
C                         THE TOTAL DELTA-P FOR THE TUBE.
C
      IF(NFINAL)3,3,1
    1 IF(PCHALL)3,3,2
    2 PRINT=1.0
    3 QS1=CAYK*SIGE*PIE*DI/3600.
      TOX1=SIGE*DIAT*ALOG(DIAT/(DI+2.*DELC))/(2.0*THERKT)
      W=WDOT/CAPN
      FJH=778.*FHH
      GJ=778.*32.2
      TUBEA=PIE*DI*DI/4.0
      GDI3=32.2*DI*DI*DI
      WL=(1.-QALSTR)*W
      WG=W-WL
      DELWL=WG/FMESH
      P=PSTAR
      T=TSTAR
      TX=T
      PX=P
      TOX=TO
      DISTX=0.0
      DPSUM=0.0
      DXSUM=0.0
      RHOGS=PSTAR/(TSTAR*R)
      CHIC1=(RHOGS/RHOL)*(FMUL/FMUG)**0.2
      CHI=SQRT((WL/WG)**1.8*CHIC1)
      CALL RLAFEG(CHI,PHI,RLP,DPLDX,A,B,C,D,E,F)
      VZERO=WL/(RHOL*TUBEA*RLP)
      WL1=WL+DELWL/2.0
      WG1=W-WL1
```

```
      IF(PRINT)5,5,4
    4 DIPRNT=12.*DI
      WRITE  (6,102)DIPRNT
      WRITE  (6,100)
    5 MESH=FMESH
      DO 8 J=1,MESH
    6 RHOGA=P/(R*T)
      CHIC1=(RHOGA/RHOL)*(FMUL/FMUG)**0.2
      CHI=SQRT(((WL1/WG1)**1.8)*CHIC1)
      CALL RLAFEG(CHI,PHI,RLP,DRLDX,A,B,C,D,E,F)
      RGP=1.-RLP
      V=WL1/(RLP*TUBEA*RHOL)
      U=WG1/(RGP*TUBEA*RHOGA)
      V2=V*V
      U2=U*U
      U2COEF=1.-0.9*CHI*W*DRLDX/(RGP*WL1)
      V2COEF=1.-0.9*CHI*W*DRLDX/(RLP*WG1)
      REGP=4.*WG1/(PIE*DI*FMUG)
      DPXF=-PHI*PHI*0.092*FMUG*FMUG*REGP**1.8/(GDI3*RHOGA)
      DPMDW1=0.9*DRLDX*CHI*W
      DPMDW2=2.0-DPMDW1/(RGP*WL1)
      DPMDW3=2.-DPMDW1/(RLP*WG1)
      DPMDW4=RHOGA*U2*RGP*DPMDW2/(32.2*WG1)
      DPMDW5=RHOL*V2*RLP*DPMDW3/(32.2*WL1)
      DPMDWX=DPMDW4-DPMDW5
      DPC1=(CPL*WL1+CPG*WG1)*T/(FJH*RHOGA)
      TOX=TX/(1.+TOX1*TOX**3)
      QS2=QS1*TOX**4
      DX1=QS2+DPC1*DPXF
      DX2=FHH-V2*V2COEF/GJ+U2*U2COEF/GJ-DPC1*DPMDWX+(U2-V2)/(2.*GJ)
      DX=DX2*DFLWL/DX1
      DP=-DPMDWX*DFLWL-DPXF*DX
      DELT=-T*DP/(FJH*RHOGA)
      IF(PRINT)7,7,9
    9 WLT=WL1*CAPN
      DISTX=DISTX+DX/2.
      WRITE  (6,101)DISTX,WLT,P,T,RHOGA,U,V,CHI,RLP,PHI,DPXF
      DISTX=DISTX+DX/2.
    7 P=P-DP
      IF(P)10,10,11
   10 MP=1
      GO TO 12
   11 T=T+DELT
      TX=T
      PX=P
      WL1=WL1+DFLWL
      WG1=W-WL1
      DPSUM=DPSUM+DP
      DXSUM=DXSUM+DX
    8 CONTINUE
      TL=TX
      TLO=TOX
      VLIO=W/(TUBEA*RHOL)
      CONSTG=4.*W/(PIE*DI*DI)
      ELSBC1=300.*CPL*CONSTG/(CAYK*SIGE)*DI
      ELSBC2=1./(TL-DTSC)**3-1./TL**3
      ELSBC=ELSBC1*ELSBC2
      BIGZ=DXSUM+ELSBC
C
      PRINT=0.0
C
```

```
      MP=0
 12 RETURN
100 FORMAT(1H ,3X,8HPOSITION,6X,2HWL,11X,1HP,11X,1HT,9X,5HRHO G,9X,
   11HU,11X,1HV,11X,1HX,11X,2HRL,6X,5HPHI G,4X,6HDPF/DX)
101 FORMAT(1H ,9F12.4,F8.5,F12.4)
102 FORMAT(1HL,71HPRINT-OUT OF STEP-BY-STEP PRESSURE DROP CALCULATIONS
   1 FOR TUBE DIAMETER=F5.3,3HIN.)
      END
```

```
$IBFTC GUIDE    DECK
C
      SUBROUTINE GUIDE(M,N,PN)
C
      DIMENSION HSLV(6,4),A(5),B(5),C(5),D(5),E(5),F(5)
      COMMON HSLV,A,ALIL,ALPHA,APRIME,ASTAR,B,BETA,BIGZ,C,CAPN,CAYH,
     1CAYK,CHI,CPG,CPL,D,DELC,DELCLH,DELCVH,DELTA,DI,DIAT,DLA,
     2DLH,DPOPLH,DPOPS,DPOPVH,DPSUM,DRLDX,DTSC,DVH,DXSUM,E,
     3ELSRC,EM2,ET,F,FHH,FLN,FMESH,FMUG,FMUL,FPRIME,GAMT04,KOL,NFINAL,
     4PANEL,PCHALL,PHI,PIE,PRES2,PSTAR,QALSTR,QS,QUAL2,QVH,R,RADW,
     5RHOC,RHOF,RHOG,RHOGS,RHOL,RHOP,RHOT,RLP,SIGE,TAU,THERKF,THERKT,TL,
     6TLO,TO,TSMALL,TSTA,TSTAR,TUBEA,T2,T3,UVH,UZERO,VBAR,VLH,VLIQ,
     7WDOT,WLH,WR,WVH,Y,ZN,KUO,VZERO,
     8  EPSL,ETAAS,FLR,FNC,FVH,PCON,THTAS,TST,WBAP
C
C     THIS SUBROUTINE CONTROLS THE ITERATIONS ON QVH AND UZERO.
C
      IF(M-1)1,1,2
    1 TO=T2
      UZERO=400.0
      DELTA=0.02
      QVH=50.0*WDOT*3600.0
      FLN=0.10
      SVEL=SQRT(32.14*ET/RHOT)
      DELTA1=2.*FPRIME*ALIL
      DELTA2=(RHOP*62.45/RHOT)**0.5
      DELTA3=(VBAR/SVEL)**0.66667
      DELTA4=(6.747E-5/RHOP)**0.3333
      CALL ENBARS(N,PN,ENBAR)
      DELTA5=(ALPHA*TAU/(ENBAR*(BETA+1.)))**(1./(3.*BETA))
      DLA=DELTA1*DELTA2*DELTA3*DELTA4*DELTA5
    2 UL=0.0
      UH=0.0
      MP=0
      CAPNS=0
      NFINAL=0.
    3 KUO=0
      L=0
    4 KQVH=0
    5 KCAPN=0
    6 CALL SUBW
      DEBUG DIAT,DELTA
    7 QALSTR=QUAL2-QVH/(FHH*WDOT*3600.0)
      IF(QALSTR)25,25,4
   40 RHOGS=PSTAR/(R*TSTAR)
    8 CAPN=4.*WDOT*QALSTR/(PIE*RHOGS*UZERO*DI*DI)
    9 QVHSV=QVH
      CALL SUBH(L)
      QVHTST=0.5*TSTA*(QVHSV+QVH)
      IF(ABS(QVHSV-QVH)-QVHTST)12,12,11
```

```
   11 KQVH=KQVH+1
      IF(KQVH-25)5,5,25
      QVHSV=QVH
   12 IF(NFINAL)10,10,71
   10 CALL SUBK(MP)
      DEBUG CAPN,BIGZ
      DELUO=100.0
      IF(MP)42,42,43
   43 DELUO=DELUO/2.0
      UZERO=UZERO-DELUO*2.0
      MP=0
      GO TO 22
   42 DPOPS1=DPSUM/PSTAR
      DPTST=0.5*TSTA*(DPSUM+DPOPS*PSTAR)
      IF(DPOPS)64,65,64
   65 DPTST=.001
   64 IF(ABS(DPOPS*PSTAR-DPSUM)-DPTST)35,35,21
   35 IF(ABS(CAPNS-CAPN)-0.5)26,26,21
   21 UZEROS=UZERO
   13 IF(DPOPS*PSTAR-DPSUM)14,14,17
   14 UZEROH=UZERO
      DPSUMH=DPSUM
      IF(UL)16,16,15
   15 UH=1.0
      GO TO 20
   16 UZERO=UZERO-DELUO
      UH=1.0
      GO TO 22
   17 UZEROL=UZERO
      DPSUML=DPSUM
      IF(UH)19,19,18
   18 UL=1.0
      GO TO 20
   19 UZERO=UZERO+DELUO
      UL=1.0
      GO TO 22
   20 DELU =UZEROH-UZEROL
      DDELP=DPSUMH-DPSUML
      DDELP1=DPSUMH-DPOPS*PSTAR
      UZERO=UZEROH-DELU *DDELP1/DDELP
   22 KUO=KUO+1
      IF(UZERO-2500.0)41,41,25
   41 IF(KUO-30)61,61,26
   61 CAPNS=CAPN
      GO TO 4
   25 KOL=1
      GO TO 34
   26 KOL=0
C
C                             THIS SECTION ROUNDS OFF THE NUMBER OF TUBES TO
C                             AN INTEGER NUMBER.
C
   30 UZEROM=UZERO
      CAPNNS=CAPN
      JCAPN=CAPN
      FCAPN=JCAPN
      IF(ABS(CAPN-FCAPN)-0.5)27,27,28
   28 CAPN=FCAPN+1.0
      GO TO 63
   27 CAPN=FCAPN
   63 FCAPNS=CAPN
```

```
29 UZERO= UZEROS-(CAPNS-FCAPNS)*(UZEROS-UZERON)/(CAPNS-CAPNNS)
   IF(UZERO-2500.0)31,31,32
32 UZERO=2500.0
31 NFINAL=1
   IF(UZERO-100.0)59,59,37
59 UZERO=100.0
37 KUO=KUO+1
   UZEROS=UZERON
   CAPNS=CAPNNS
   IF(KUO-50)60,60,25
60 UZERON=UZERO
   GO TO 6
71 CAPNNS=CAPN
   IF(ABS(CAPN-FCAPNS)-.001) 33,33,29
33 L=1
   CAPN=FCAPNS
   CALL SUBK(MP)
   CALL SUBH(L)
34 RETURN
   END
```

```
$IBFTC SUBH     NOLIST,NOREF,DECK
C
       SUBROUTINE SUBH(L)
       DIMENSION HSLV(6,4),A(5),B(5),C(5),D(5),E(5),F(5)
C
       COMMON HSLV,A,ALIL,ALPHA,APRIME,ASTAR,B,BETA,BIGZ,C,CAPN,CAYH,
      1CAYK,CHI,CPG,CPL,D,DELC,DELCLH,DELCVH,DELTA,DI,DIAT,DLA,
      2DLH,DPOPLH,DPOPS,DPOPVH,DPSUM,DRLDX,DTSC,DVH,DXSUM,E,
      3ELSBC,EM2,ET,F,FHH,FLN,FMESH,FMUG,FMUL,FPRIME,GAMT04,KOL,NFINAL,
      4PANEL,PCHALL,PHI,PIE,PRES2,PSTAR,QALSTR,QS,QUAL2,QVH,R,RADW,
      5RHOC,RHOF,RHOG,RHOGS,RHOL,RHOP,RHOT,RLP,SIGE,TAU,THERKF,THERKT,TL,
      6TLO,TO,TSMALL,TSTA,TSTAR,TUBEA,T2,T3,UVH,UZERO,VBAR,VLH,VLIQ,
      7WDOT,WLH,WR,WVH,Y,ZN,KUO,VZERO,
      8  EPSL,ETAAS,FLR,FNC,FVH,PCON,THTAS,TST,WBAR
C
C                           THIS SUBROUTINE SETS THE VALUES OF M1, M2, M3,
C                           DEPENDING UPON THE NUMBER OF PANELS. IT THEN
C                           FINDS THE HEADER SIZES,QVH, AND THE RADIATOR
C                           COMPONENT WEIGHTS.
C
       IF(L)1,1,6
     1 IF(PANEL-2.0)2,3,4
     2 FM1=1.0
       FM2=1.0
       FM3=1.0
       GO TO 5
C
     3 FM1=2.0
       FM2=0.5
       FM3=1.0
       GO TO 5
C
     4 FM1=1.0
       FM2=0.5
       FM3=0.5
C
     5 Y=2.0*FM2*CAPN*(FLN+0.5*DI+DELC+DELTA)
       DVHC1=0.00357*Y*FMUG**0.2
       DVHC2=(2.*WDOT*QUAL2*FM1)**1.8*FM1
       DVHC3=RHOG*PRES2*DPOPVH*PIE**1.8
       DVH=(DVHC1*DVHC2/DVHC3)**(1./4.8)
       FVH=0.85
       QVH=2.0944*SIGE*FVH*Y*DVH*T2**4
       GO TO 9
     6 DLH=(2.0*FM3*WDOT/(PIE*RHOL*VLH))**0.5
       RELH2=(RHOL*DLH*VLH/FMUL)**0.2
       DPLH=0.00051*RHOL*VLH*VLH*FM1*Y/(RELH2*DLH)
       DPOPLH=DPLH/(PSTAR-DPSUM)
       DELCLH=0.04*DLH
       IF(DELCLH-0.01)8,8,7
     7 DELCLH=0.01
     8 WVH1=(DVH+DELCVH)*(Y     +DELCVH)*DELCVH*RHOC
       WVH2=(DVH+2.*DELCVH+DELTA)*(Y     +2.*DELCVH+DELTA)*RHOT*DELTA
```

```
      WVH=0.666667*3.1415926*(WVH1+WVH2)
      WLH1=RHOL*DLH*DLH/4.0+RHOC*DELCLH*(DLH+DELCLH)
      WLH2=RHOT*DELTA*(DLH+DELTA+2.*DELCLH)
      WLH=Y*(WLH1+WLH2)*PIE/EM2
      WP1=RHOC*DELC*(DI+DELC)
      WP2=RHOT*DELTA*(DI+2.*DELC+DELTA)
      WP3=4.0*1.713E-09*RHOF*(FLN*TO)**3/THERKF
      WR=CAPN*BIGZ*(WP3+PIE*(WP1+WP2))
      RADW=WVH+WLH+WP
      UVH=EM1*2.*WDOT*QUAL2/(DVH*DVH*RHOG*PIE)
    9 RETURN
      END
```

```
$IBFTC RLAFEG   NOLIST,NOREF,DECK,DEBUG
C
      SUBROUTINE RLAFEG(CHI,PHI,RLP,DRLDX,A,B,C,D,E,F)
C
      DIMENSION HSLV(6,4),A(5),B(5),C(5),D(5),E(5),F(5)
C
C    THIS  SUBROUTINE  IS  THE  CURVE  FIT  SUBROUTINE  FOR  THE  RL
C     AND  PHI-G  CURVE FITS.
C
      IF(CHI-100.)1,1,2
    1 ELX=ALOG10(CHI)
      IF(.001-CHI)3,3,5
    5 NA=0
      GO TO 6
    3 NA=4.+ELX
      GO TO 6
    2 CHI= 99.99
      GO TO 1
    6 IF(NA)7,7,8
    7 PHI=1.0
      DFEGDX=0.
      GO TO 11
    8 PHI=ELX*(ELX*A(NA)+B(NA))+C(NA)
      PHI=10.0**PHI
C
C     RL  VERSUS  CHI  CURVE  FIT  FROM  THIS  POINT  ON.
C
   11 IF(NA)12,12,13
   12 RLP=10.**ELX
      DRLDX=10.**ELX/CHI
      GO TO 14
   13 RLP=ELX*(ELX*D(NA)+E(NA))+F(NA)
      RLP=10.**RLP
      DRLDX=RLP*(2.*ELX*D(NA)+E(NA))/CHI
   14 RETURN
      END
$IBFTC HSFIT   NOLIST,NOREF,DECK
      FUNCTION HSFIT(T,J)
C
C
      DIMENSION HSLV(6,4)
C
      COMMON HSLV
C
C     THIS  SUBROUTINE OR PROGRAM FUNCTION IS THE ENTHALPY AND ENTROPY
C    CURVE FIT.
C
C
       X          =HSLV(1,J)+T*(HSLV(2,J)+T*(HSLV(3,J)+T*(HSLV(4,J)
     1+T*(HSLV(5,J)+T*(HSLV(6,J))))))
      HSFIT=X
C
```

```
      RETURN
      END
$IBFTC ENBARS  NOLIST,NOREF,DECK
      SUBROUTINE ENBARS (N,POFN,ENBAR)
      DIMENSION PATCH (20)
C     DIMENSION PATCH (20)
      IF (N) 1,1,2
    1 ENBAR= -ALOG(POFN)
      GO TO 3
    2 IF (N-2) 4,5,5
    4 DFLP = 1.0- POFN
      ENBAR= SQRT( -2.0* ALOG(POFN))
   13 FMINN = EXP(-ENBAR)
      IF (DFLP - .005) 6,6,7
    7 EFOP = (1.0+ ENBAR) * FMINN - POFN
      GO TO 8
    6 ALFK = .5 * ENBAR ** 2
      FOP = ALFK
      CJM2 = 1.
      CJM1 = 2.
      DO 9 J = 3,16
      IF (ABS(ALFK/FOP) - 1.E-10) 8,8,1
   10 CJ = J
      ALFK = -ALFK * CJM1 * ENBAR / CJ / CJM2
      FOP = FOP + ALFK
      CJM2 = CJM1
    9 CJM1 = CJ
      EFOP = FOP - DFLP
    8 EFPRIM = - ENBAR * FMINN
      FOFP = EFOP/EFPRIM
      IF (ABS(FOFP/ENBAR) - 5.E -5) 3,3,11
   11 ENBAR = ENBAR - FOFP
      GO TO 13
    5 WRITE (6,12)
    3 RETURN
   12 FORMAT (17HK N IS TOO LARGE )
      END
```

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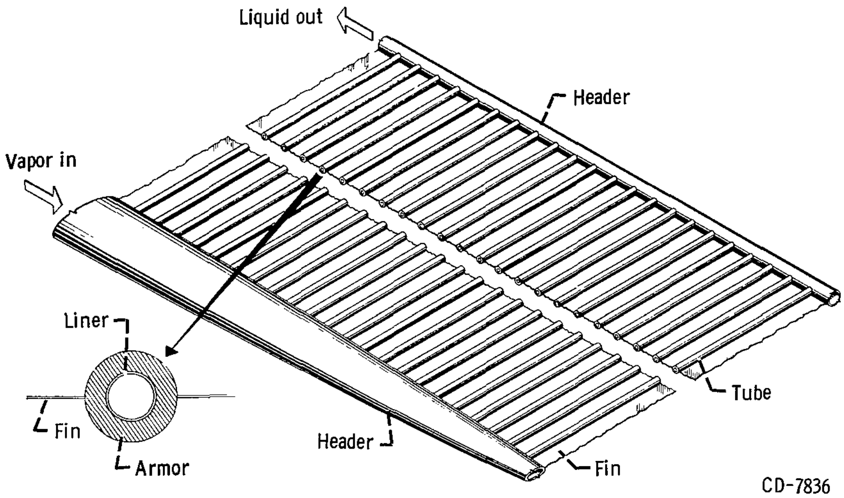

Figure 1. - Plane finned-tube direct-condensing radiator.

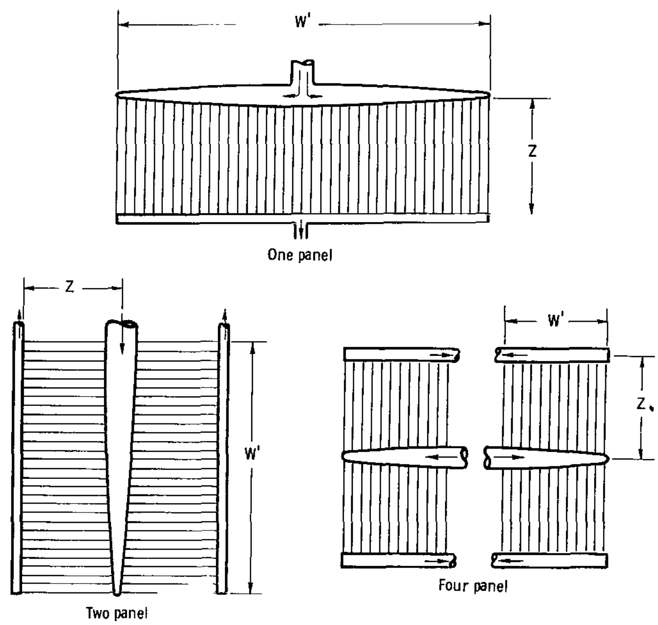

Figure 2. - Panel configurations.

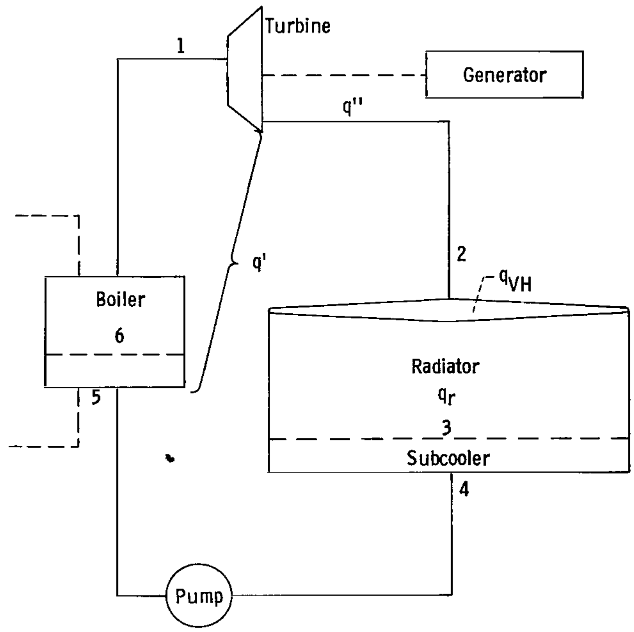

Figure 3. - Simple Rankine cycle electric power generating system.

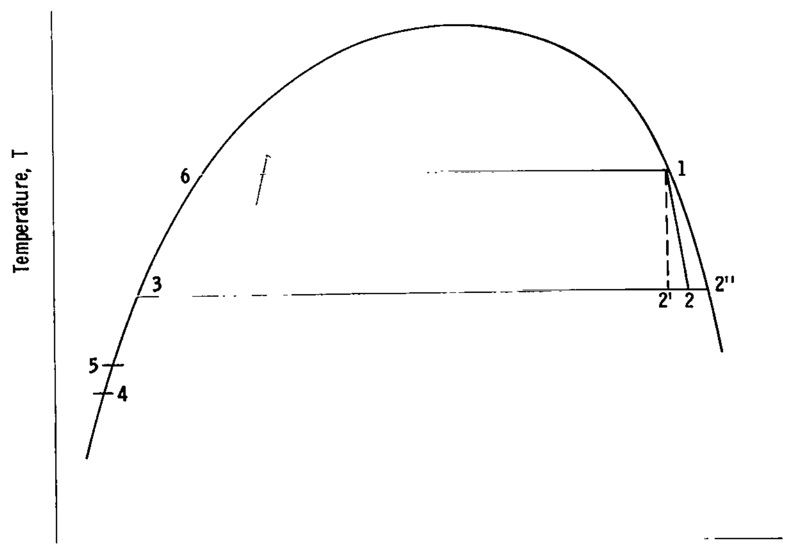

Figure 4. - Temperature-entropy diagram without pressure drop in radiator.

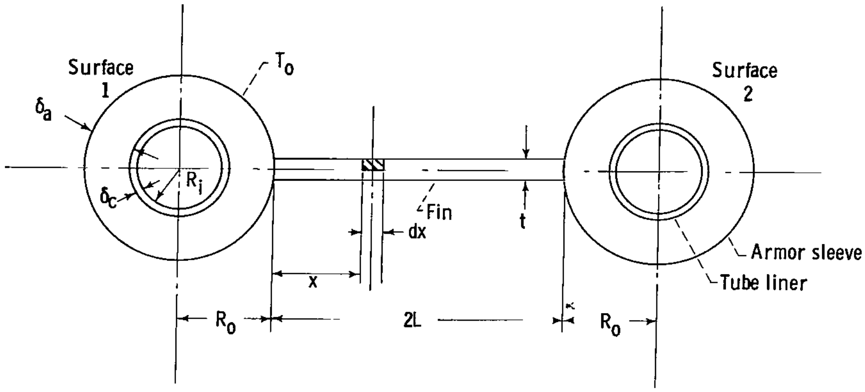

Figure 5. - Schematic drawing of finned-tube assembly.

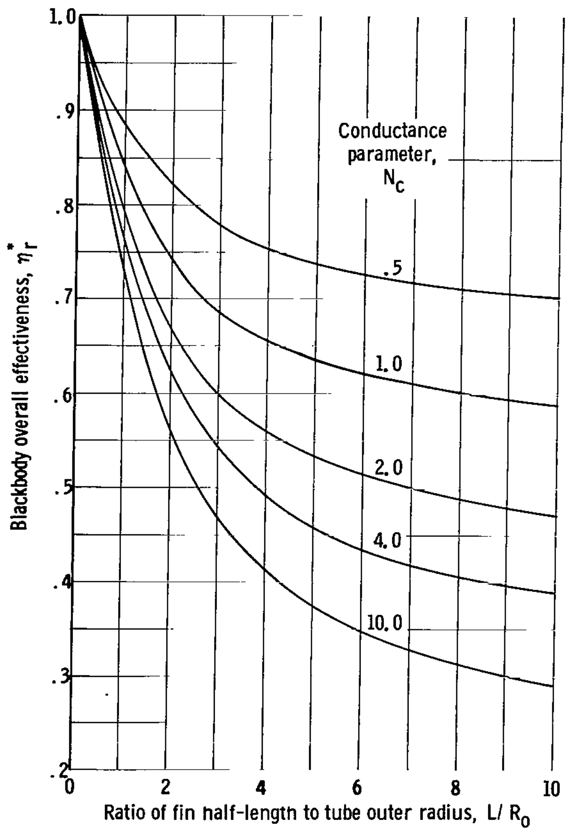

Figure 6. - Example of blackbody overall effectiveness for central fin and tube.

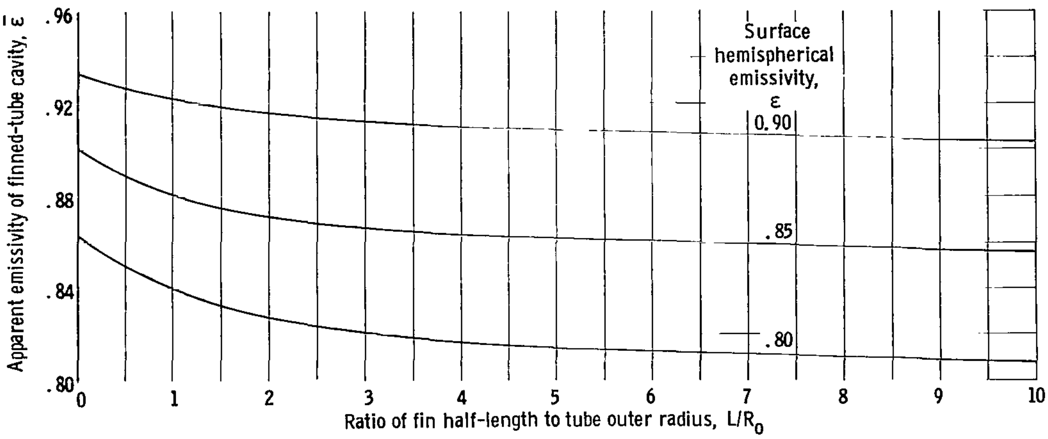

Figure 7. - Apparent emissivity of an isothermal central finned-tube cavity.

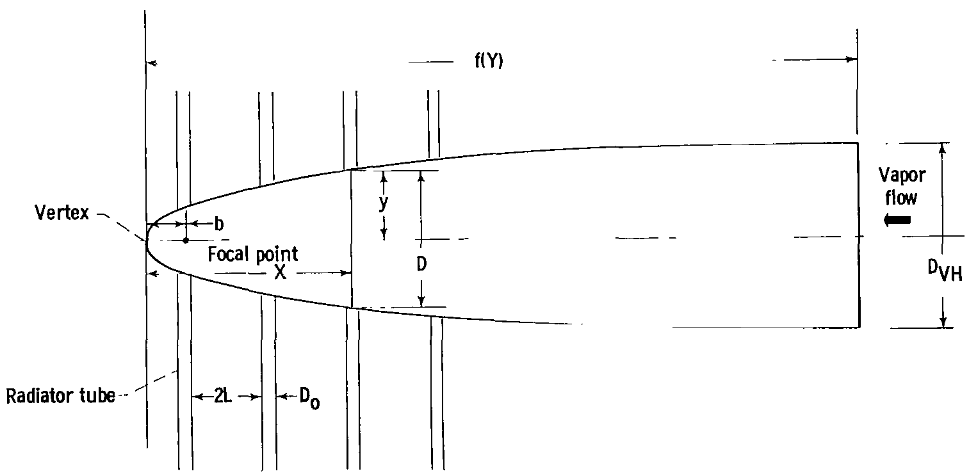

Figure 8. - Detail of parabolic header geometry.

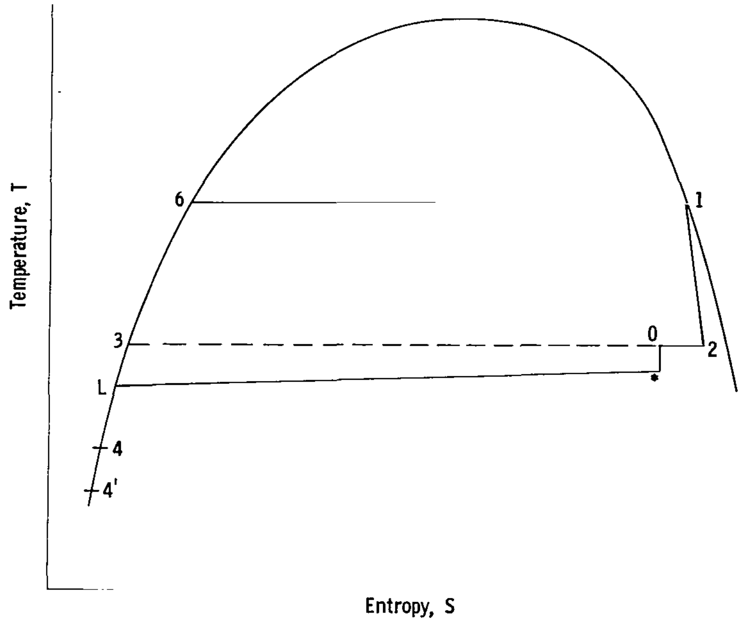

Figure 9. - Rankine cycle temperature-entropy diagram with pressure drop in radiator.

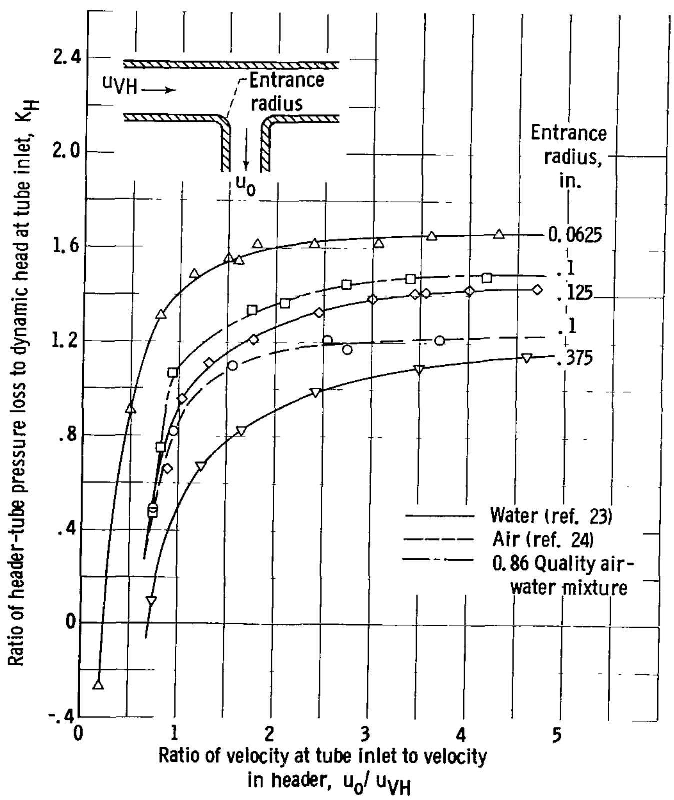

Figure 10. - Effect of header and tube velocities and radius of curvature at tube inlet on header-tube pressure drop (refs 23 and 24).

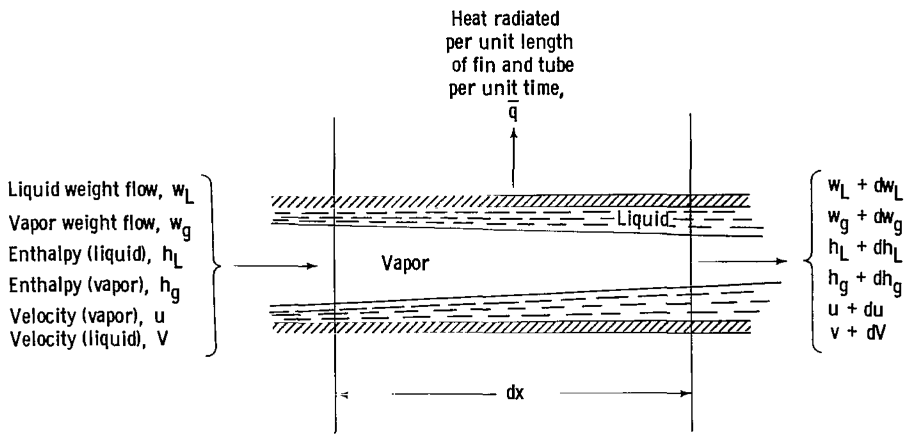

Figure 11. - Radiator tube two-phase flow model.

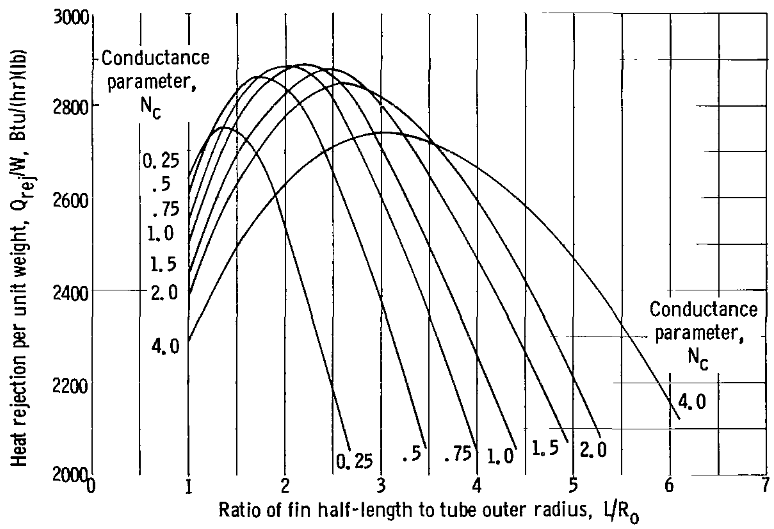

Figure 12. - Parametric Program radiator total heat rejection per unit weight as function of ratio of fin half-length to tube outer radius for several values of conductance parameter. Radiator panel temperature, 1700° R; power output 1 megawatt; tube inside diameter, 1 inch; fin and armor material, beryllium.

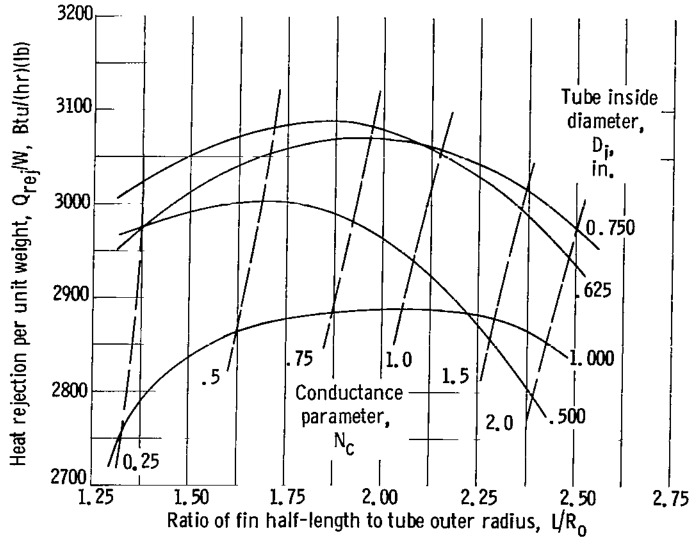

Figure 13. - Performance map for Parametric Program radiator peak heat rejection per unit weight. Radiator temperature, 1700° R; power output, 1 megawatt; fin and armor material, beryllium.

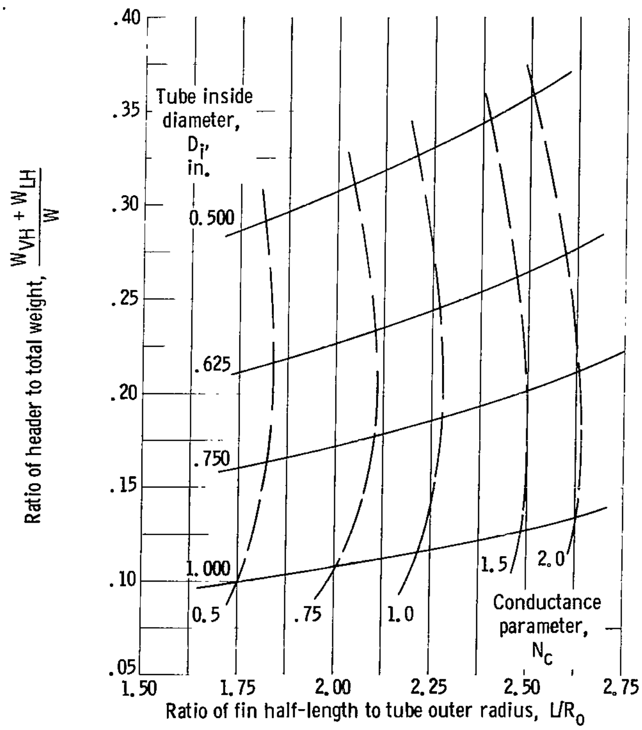

Figure 14. - Ratio of header weight to total radiator weight at peak heat rejection per unit weight for each tube diameter (Parametric Program).

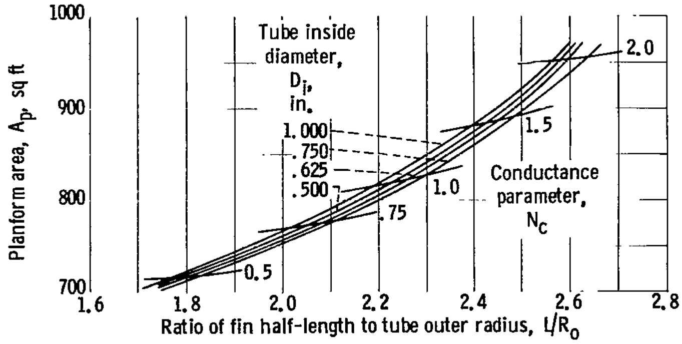

Figure 15. - Radiator planform area requirements (Parametric Program).

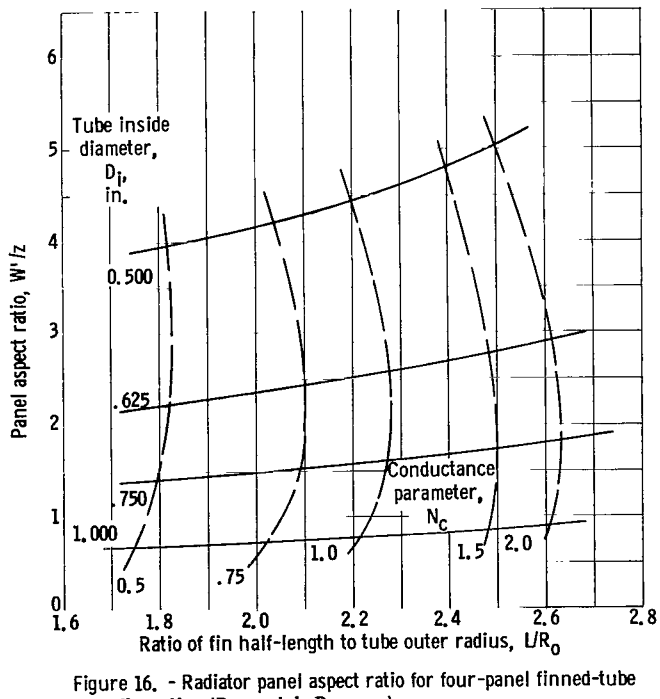

Figure 16. - Radiator panel aspect ratio for four-panel finned-tube configuration (Parametric Program).

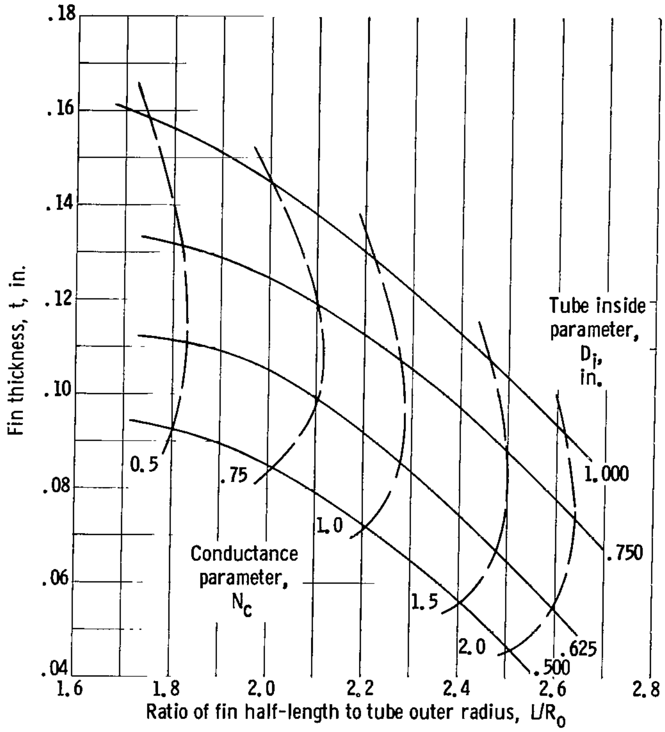

Figure 17. - Radiator fin thickness at peak heat rejection per unit weight for four-panel finned-tube configuration (Parametric Program).

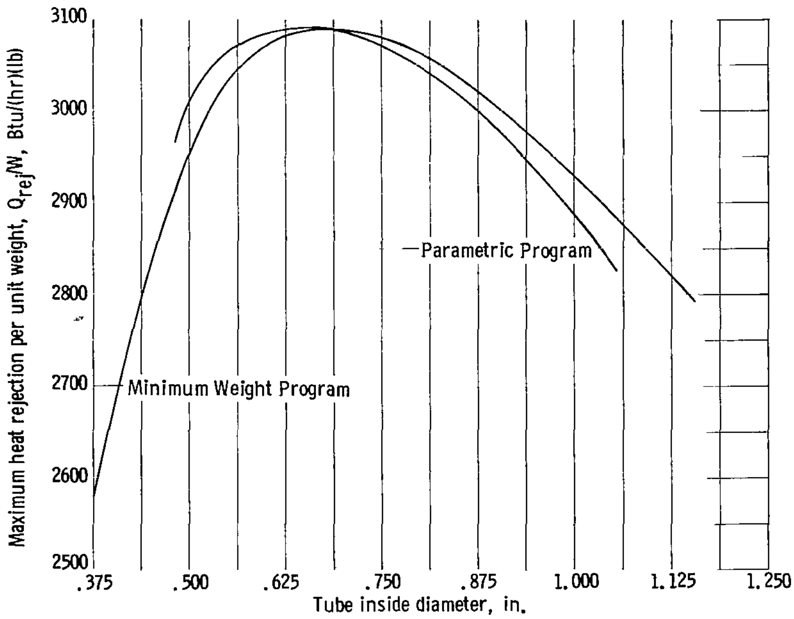

Figure 18. - Comparison of radiator heat rejection per unit weight obtained from Parametric and Minimum Weight Programs.

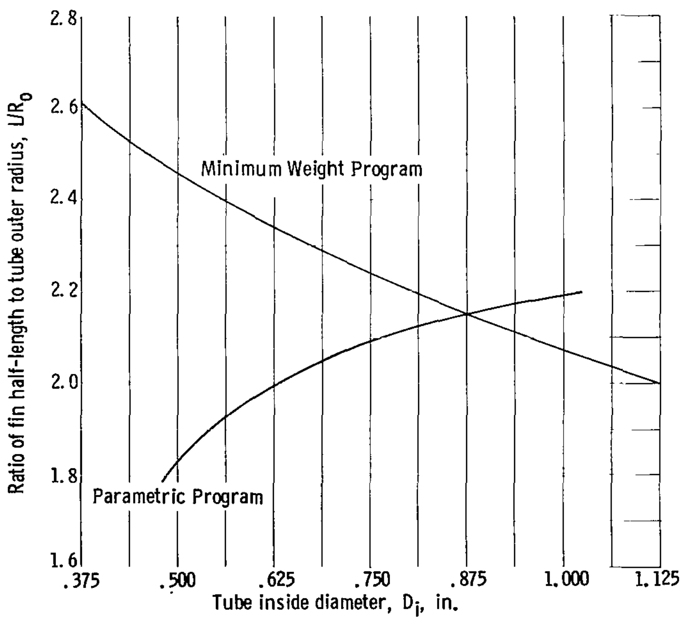

Figure 19. - Comparison of ratio of fin half-length to tube outer radius obtained for maximum heat rejection per unit weight from Parametric Program and that obtained for product of emissivity and conductance parameter equal to 0.9 from Minimum Weight Program.

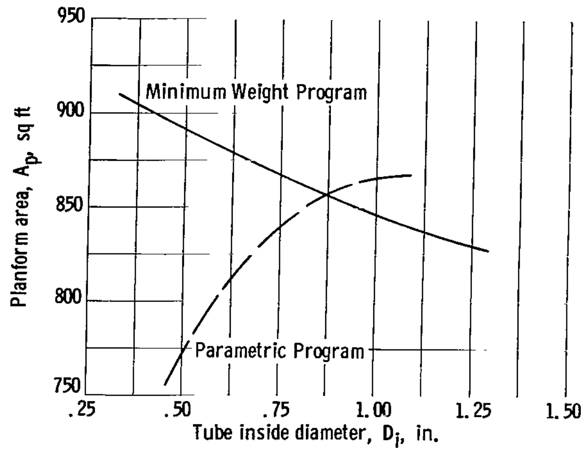

Figure 20. - Comparison of radiator planform area obtained from Parametric and Minimum Weight Programs.

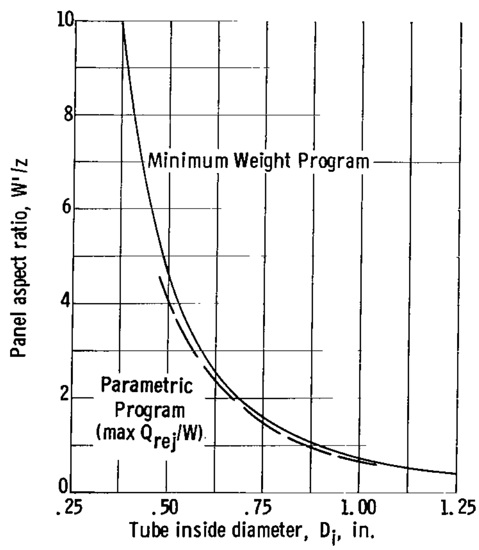

Figure 21. - Comparison of panel aspect ratios of Parametric and Minimum Weight Programs.

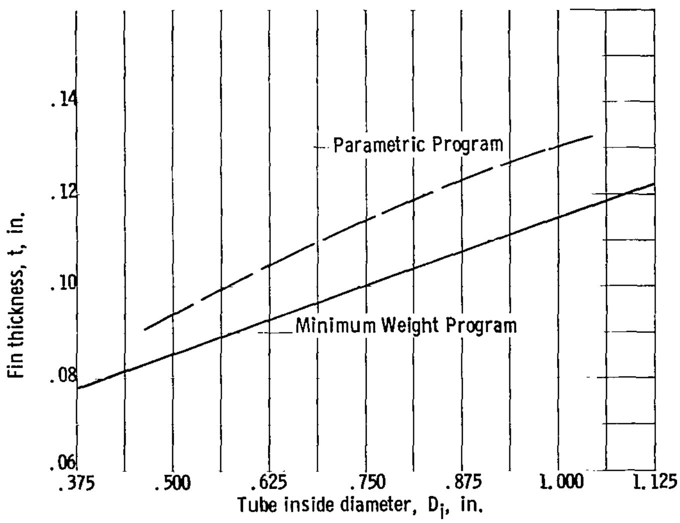

Figure 22. - Comparison of fin thickness at maximum heat rejection unit weight for Parametric and Minimum Weight Programs.

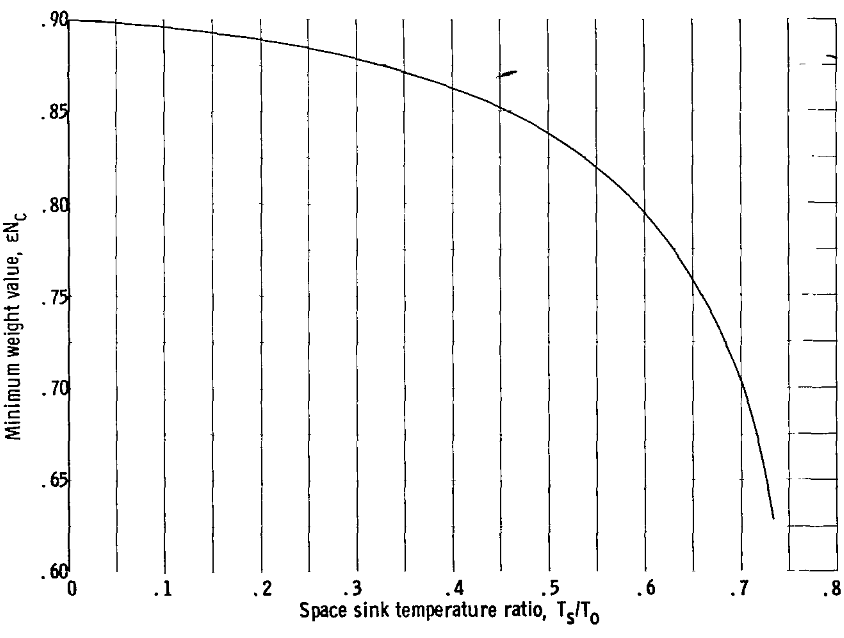

Figure 23. - Effect of sink temperature on value for Minimum Weight (Minimum Weight Program).

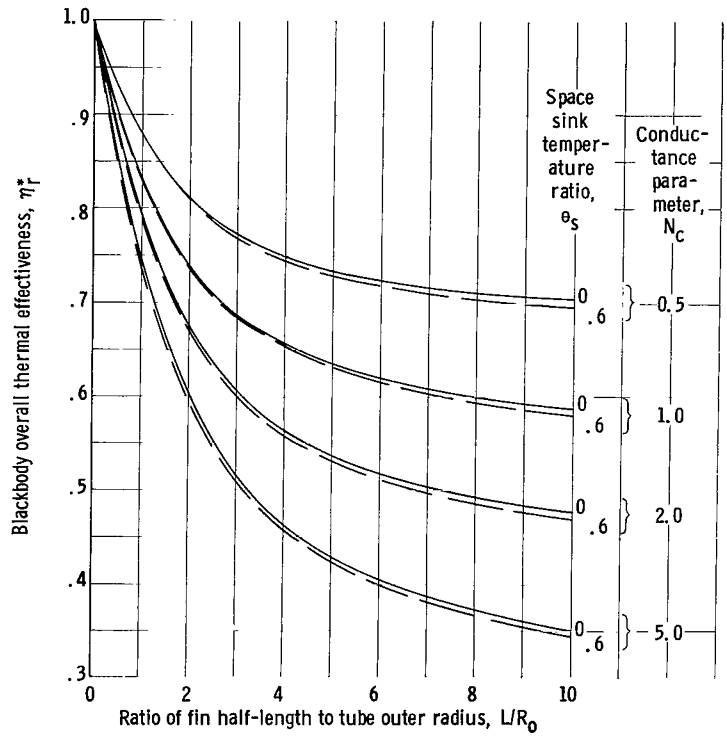

Figure 24. - Effect of sink temperature on finned-tube thermal effectiveness.

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